BBC RD 1984/9

RESEARCH DEPARTMENT

REPORT

Satellite Broadcasting: The performance of C–MAC in a hardware simulation of a DBS transmission chain

P. Shelswell, M.A., C.Eng., M.I.E.E.

Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION September 1984

BBC RD 1984/9
621.396.946:
621.397.13

SATELLITE BROADCASTING: THE PERFORMANCE OF C-MAC IN A HARDWARE SIMULATION OF A DBS TRANSMISSION CHAIN

P. Shelswell, M.A., C.Eng., M.I.E.E.

Summary

This report describes a series of experiments and gives details of measurements of C-MAC, a new transmission standard for direct broadcasting by satellite, when passed through a hardware simulation of a complete satellite transmission chain.

The quality of the vision and sound (or digital data) were monitored throughout the chain, for the nominal chain and for the chain with deliberately introduced impairments such as noise, interference, amplitude and group-delay distortion and non-linear amplification.

It is concluded that C-MAC is a suitable transmission standard for satellite broadcasting.

Issued under the Authority of

M.E.B. Moffat

Head of Research Department

Research Department, Engineering Division,
BRITISH BROADCASTING CORPORATION
September, 1984
(RA-217)

This Report may not be reproduced in any form without the written permission of the British Broadcasting Corporation.

It uses SI units in accordance with B.S. document PD 5686.

SATELLITE BROADCASTING: THE PERFORMANCE OF C-MAC IN A HARDWARE SIMULATION OF A DBS TRANSMISSION CHAIN

Section Title Page

Summary .... Title Page

1. Introduction 1

2. Experimental configuration 2

3. Experimental work 4

  3.1. Vision tests 4
    3.1.1. Subjective appraisal 4
    3.1.2. Noise measurements 4
    3.1.2.1. Basic measurements 5
    3.1.2.2. Effect of a.m. to p.m. conversion 6
    3.1.2.3. *Noise spectrum and effect of carrier-frequency offset* 7
    3.1.3. Video waveform measurements 8
    3.1.4. Baseband amplitude/frequency response 13
  3.2. Data tests 15
    3.2.1. The spectrum of 2-4 PSK 15
    3.2.2. Error performance of the data channel 20
    3.2.2.1. BER of the unimpaired signal 20
    3.2.2.2. BER of signals with deliberate distortion 23
    3.2.2.3. Effect of frequency offset of transponder filters on BER 26
    3.2.3. Subjective appraisal 26
    3.2.4. A comment on the suitability of 2-4 PSK for DBS 27
  3.3. Interference 28
    3.3.1. Effect of interference to the vision 29
    3.3.2. Effect of interference on the data 30
    3.3.3. The effects of interference on the spectrum 30

4. Conclusions 33

5. Acknowledgements 33

6. References 33

© BBC 2006. All rights reserved. Except as provided below, no part of this document may be reproduced in any material form (including photocopying or storing it in any medium by electronic means) without the prior written permission of BBC Research & Development except in accordance with the provisions of the (UK) Copyright, Designs and Patents Act 1988.

The BBC grants permission to individuals and organisations to make copies of the entire document (including this copyright notice) for their own internal use. No copies of this document may be published, distributed or made available to third parties whether by paper, electronic or other means without the BBC's prior written permission. Where necessary, third parties should be directed to the relevant page on BBC's website at http://www.bbc.co.uk/rd/pubs/ for a copy of this document.

SATELLITE BROADCASTING: THE PERFORMANCE OF C-MAC IN A HARDWARE SIMULATION OF A DBS TRANSMISSION CHAIN

P. Shelswell, M.A. C.Eng., M.I.E.E.

1. Introduction

This report describes a series of experiments in which C-MAC signals were transmitted through a hardware simulation of a complete satellite chain.

C-MAC/packet is a new transmission standard for direct broadcasting by satellite (DBS) developed by the European Broadcasting Union (EBU)[1] from a proposal originally made by the Independent Broadcasting Authority (IBA). In this system, the luminance and colour difference components of the television picture are time multiplexed together with a sound/data burst on a line-by-line basis. To achieve this the luminance and colour difference components must be time compressed. The vision signal is transmitted by frequency modulation of the carrier and the sound/data signal is transmitted in packets using 2-4 PSK digital modulation.[2]

The new C-MAC* standard has been shown to provide an improvement of both the sound and picture quality. The picture quality is improved because of the absence of the cross-colour and cross-luminance effects, prevalent in the PAL, NTSC and SECAM systems. This allows a full 5.5 MHz luminance resolution to be achieved without penalty. The digital transmission of sound permits high-quality reception with minimal degradations. The improvements in quality have been demonstrated by the EBU, both using transmissions through the Orbital Test Satellite (OTS) and using simple radio-frequency simulations.

It is important that the signal quality remains high even when the effects of transmission impairment are included. Linear distortions can arise anywhere in the chain, whilst non-linear distortions can be introduced by the high-power amplifiers in the earth station and the satellite. Ideally, no significant degradation of the signal should be introduced by the broadcaster and it should be possible to achieve good quality reproduction using non-critical receiver techniques. The choice of a time multiplex format has removed many of the imperfections found in frequency multiplex systems such as PAL, NTSC and SECAM.

The EBU study to identify the sources of degradation and to quantify the effects has been mainly theoretical with much of it based on computer simulation. Such experimental work as has been conducted has used a somewhat simplistic channel model. There is, therefore, a need for experimental proof that C-MAC is not degraded significantly by the channel imperfections normally expected.

In addition to the question of signal quality, there are also regulatory requirements to be considered. In particular the signal transmitted must not cause more interference than the reference in the WARC Plan[3]. In general the MAC vision signal is the limiting factor for co-channel interference and the data signal for interference to other transmissions outside the channel. The EBU studies concentrated on co-channel and adjacent-channel interference (c.c.i. and a.c.i.) in the down-link. Although there is as yet no plan for the up-link, it is also desirable to know the effect of interference on the up-link, and how the effect varies with satellite parameters.

It was therefore desirable to test C-MAC signals passing through a complete satellite chain. To be completely satisfactory the channel under test should include all the components encountered in a real DBS system. However, it is difficult to carry out a full programme of tests with a live orbiting satellite because of the difficulty of maintaining accurate system calibration and the possibility of changing propagation conditions affecting the results.

Fortunately British Aerospace were able to provide a breadboard satellite transponder[4] for these tests. This was a two-channel system which had input and output multiplex (IMUX and OMUX) filters, with frequency translation of 5.6 GHz and two low-power (20 W) travelling-wave-tube amplifiers (TWTAs).

It was therefore possible to test C-MAC through hardware representative of a complete DBS chain. The breadboard transponder, together with the BBC's transportable satellite earth-station[5] (which acted both as feeder link and receiver) and a C-MAC codec, enabled a complete transmission chain to be reproduced in the laboratory. As a result, the effect of the transmission system could be measured without the problems associated with the reception of a live satellite.

---

* In this report we are only concerned with the vision and digital sound/data modulation systems and not the form of digital multiplexing; thus the '/packet' suffix will be dropped in further discussion.

This report describes the results of a series of experiments using this complete model of a satellite system. The objectives were:

1. to measure the quality of the MAC vision signal and the 2-4 PSK data signal in a nominally undistorted channel,
2. to measure the sensitivity of the vision and data signals to channel degradations,
3. to examine the effects of interference and noise.

2. Experimental configuration

The experimental equipment was assembled to model a complete DBS transmission chain. Because of the large number of different experiments there were several different configurations. However, the nominal system is shown in Fig. 1.

The signal source generated C-MAC at an intermediate frequency (i.f.) of 70 MHz. As the EBU C-MAC specification had not been produced at the time of these experiments, the equipment operated according to an earlier, UK specification. The significant differences between the two specifications are:

1. The earlier specification allowed colour difference signals of 1.3 V peak-peak rather than limiting them to 1.0 V peak-peak (the same signal gain is used in both cases).
2. The data multiplex was not locked to the video frame. It was a packet multiplex developed originally for use on a digital subcarrier in conjunction with a PAL video signal.
3. The timing of the time-division structure was slightly different.
4. There was no service-identification system.

However, none of these differences could give rise to any significant difference in the results of the experiments if performed for the EBU system, save perhaps for the absence of high-level colour difference signals, and a difference in subjective sound quality for a given bit error ratio in the data channel.

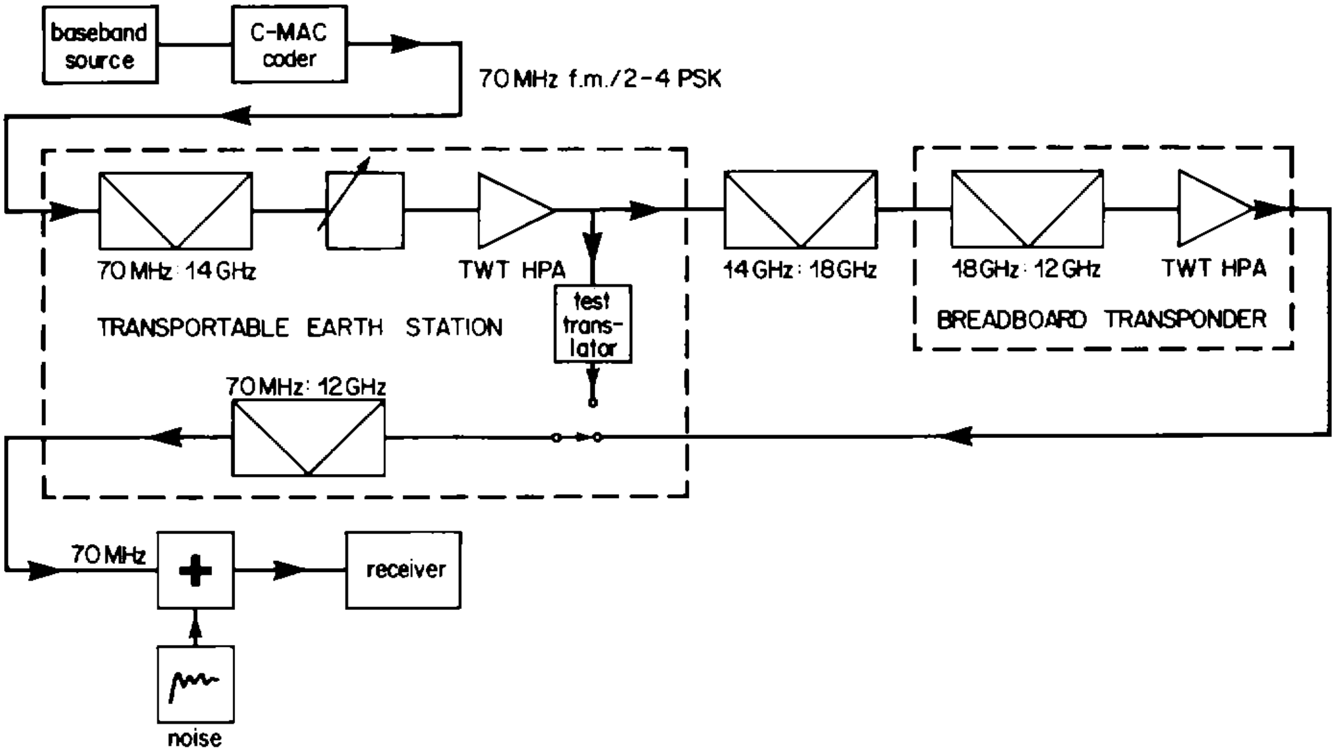

Fig. 1 – Experimental configuration.

The video signal sources available were colour component signals from a slide scanner, luminance signals from a waveform generator (providing standard PAL waveforms without synchronisation pulses or colour burst), and frequency sweeps from a network analyser. The sound/data channel carried either sound taken off-air from the BBC v.h.f. radio network, and digitally encoded, or else a pseudo-random binary sequence (p.r.b.s.).

The DBS earth-station was modelled by the BBC's transportable earth-station[5]. This accepted the 70 MHz i.f. signal from the C-MAC coder and converted it to 14 GHz before amplification in a high power (600 W) TWTA. The drive level to the TWTA could be varied, thus providing control of the operating point of the TWT itself.

The earth-station provided an output at 14 GHz which was upconverted to 18 GHz to provide a suitable input for the breadboard transponder. This upconverter is not found in a conventional DBS chain and so was engineered to be wideband and linear.

The 18 GHz signal was attenuated and fed directly into the breadboard transponder. The transponder was a complete electrical model of a 2-channel satellite communications payload excepting the antenna hardware. The first stage was a wideband filter followed by a low-noise amplifier. This selected the up-link transmissions and rejected, in particular, interference at the transponder output frequencies. The incoming signal was then downconverted by 5.6 GHz to the desired DBS transmission frequency. After further wideband amplification the signal was passed to an input multiplex filter (IMUX). This selected the individual channels and routed them to separate TWTAs (in this transponder the channels were aligned for channels 3 and 7 which are centered on 11.76584 and 11.84256 GHz respectively). After amplification the two separate channels were combined by output multiplex filters (OMUX) to create the signal which would have been broadcast. The signal level in the TWT could be adjusted using an attenuator at the input to the satellite transponder.

Instead of radiating the 12 GHz signal, it was attenuated and returned directly to the transportable earth-station for downconversion to the i.f. frequency of 70 MHz.

The 70 MHz i.f. signal was then passed to the C-MAC decoder for demodulation. The decoder used a limiter-discriminator demodulator for the vision signals and a delay-line differential demodulator for the 2-4 PSK signals.

After demodulation the signal could be monitored in several ways. The vision signal could be viewed on a high-quality picture monitor. Test waveforms could be monitored on an oscilloscope or an automatic video waveform analyser (BBC type ME2M/502). The data channel could be analysed by monitoring the errors, or by decoding the packet multiplex and listening to the recovered sound signal on a high-quality loudspeaker.

In addition to the complete transmission chain (the transponder loop) there were several modifications available to provide test facilities. They were:

1. I.f. loop : In this test condition the 70 MHz source and the 70 MHz receiver were connected directly. This bypassed all the radio-frequency (r.f.) circuits and provided a reference condition.

2. Earth-station loop : In this test condition the breadboard transponder was by-passed. The 14 GHz signal at the output of the earth-station was downconverted to the output frequency of the breadboard transponder using a wideband, linear test-translator.

3. Addition of another channel : It was possible to generate a second C-MAC channel at 14 GHz using the spare equipment from the transportable earth-station and another C-MAC coder, and to add this to the attenuated output from the earth-station (before linear upconversion to 18 GHz). The channel frequency was adjustable, so it was possible to provide a signal for the second channel in the satellite transponder, or alternatively c.c.i., a.c.i. or second-adjacent channel interference to the wanted channel on the up-link. Only one signal could be amplified by a TWTA in the earth-station, so for interference measurements it was necessary to decide which of the two channels, wanted or unwanted, should be subjected to the effect of the earth-station amplifier chain.

4. Addition of noise : It was possible to add noise to the signal at 70 MHz, either at source or in the receiver. The noise source provided a known noise power, evenly distributed over at least 40 MHz bandwidth.

5. Addition of distortion : It was possible to distort the amplitude and group-delay response of the i.f. channel at 70 MHz. The equipment allowed calibrated amounts of distortion to be introduced in steps, giving linear or parabolic, amplitude or group-delay distortions in any combination.

3. Experimental work

3.1. Vision tests

3.1.1. Subjective appraisal

In a satellite channel the most obvious vision degradation is usually noise. This is mainly introduced in the front-end of the domestic receiver, although under exceptional conditions noise on the up-link may also be significant.

As MAC was a new transmission standard there was little previous experience as to its sensitivity to types of degradation other than noise. An important test was therefore a subjective appraisal of the quality of MAC after it had passed through the complete system. This was carried out using the basic transponder loop and also with the introduction of severe channel distortion*. The same procedure was repeated using the 70 MHz i.f. loop as a reference. The picture source in this experiment was Test Card F.

The subjective tests showed that noise was the dominant impairment. In the absence of noise, the only evidence of any picture impairment was a slight loss of contrast in the highest-frequency luminance grating in Test Card F when full distortion was applied (either using the complete transmission chain or the i.f. loop). When noise was added to the 70 MHz i.f. input to the C-MAC decoder, the noise visibility on the demodulated picture was a function of the carrier-to-noise ratio† (C/N). There was insufficient time to complete a formal series of subjective tests. However, an informal assessment indicated that the noise on the picture became perceptible at a C/N of about 20 dB. Reduction in C/N made picture noise progressively more visible, showing a wormy character, until f.m. threshold was reached.

Threshold spikes first appeared in the undistorted channel at a C/N of about 10.5 dB (see Table 1). However, in the presence of distortion, the noise threshold occurred at higher C/N. The mechanism for this is a conversion of frequency modulation to amplitude modulation giving lower instantaneous carrier powers especially at times when high-level signals at high modulation frequencies are transmitted; (for example, threshold spikes first became visible in the frequency gratings of Test Card F). This effect is reduced when a saturating amplifier is present after the point at which the distortion is introduced but before significant noise is added. The point at which the picture was degraded to a quality grade of 1.5 on the CCIR 5-point quality scale is also recorded in Table 1. This is arbitrarily called the failure point and usually occurred at about 3 dB C/N.

Total loss of picture occurred when the synchronisation failed. The points at which synchronisation failed, or could be acquired, are functions of the search algorithm and the performance of the data channel. The performance of the data channel is discussed in Section 3.2. With the equipment used in these tests, the synchronisation appeared to fail well after picture failure, although acquisition was much closer to the picture failure point. Other search algorithms would permit acquisition of synchronisation at worse error rates, but with a higher probability of false acquisition.

3.1.2. Noise measurements

In DBS transmissions the major picture degradation is noise. Most of the noise in a practical system will be added by the head amplifier in the domestic outdoor unit. If a high-quality receiving installation is used, then the satellite's noise contribution will become significant. The main noise source in a satellite transponder is the input amplifier, but this noise is exacerbated by the phenomenon of a.m. to p.m. conversion in the TWT.

Tests were carried out to investigate the effect of noise addition both in a linear system and in a non-linear system (including a.m. to p.m. conversion). During these tests it was noticed that the results depended on the carrier frequency of the f.m. signal so this effect was investigated further. Measurements were also made to see if

---

* Severe distortion was the worst available mixture of linear and parabolic amplitude and group-delay distortion, i.e. 0.3 dB/MHz, 0.045 dB/MHz^2, 0.6ns/MHz and 0.15ns/MHz^2. The parabolic distortions are defined as an amplitude or group-delay response which varies as the square of the frequency offset from channel centre. The level of distortion (dB or ns) is defined by the constant of proportionality.

† In this report the noise bandwidth for all carrier-to-noise measurements is 27 MHz.

TABLE 1 – Carrier-to-noise ratios for given subjective imperfections to be observed (dB)

System	Vision performance				Sound performance*	
	Threshold first observed	Failure			First clicks	Failure (grade 1.5)
		picture (grade 1.5)	lock lost	lock acquired		
i.f. loop	10.5	3.5	0.0	2.5	8.0	7.0
i.f. loop with full distortion	15.3	5.3	–	1.3	13.2	11.0
transponder loop with	10.7	2.7	−2.7	2.7	7.7	6.7
transponder loop with full distortion	11.7	2.7	−0.7	4.7	9.7	6.7

* Not fully representative of the EBU specification (see Section 3.2.3).

periodic or impulsive noise was present. No periodic or impulsive noise could be detected.

3.1.2.1. Basic measurements

In the tests the signal source was a fixed oscillator. The system outlined in Section 2 was used with the earth-station operating in a linear mode (the TWT was operated with 10 dB OBO*) and the transponder at 1 dB IBO** (the normal operating point of the transponder). The received signal was demodulated, de-emphasised and low-pass filtered (8.4 MHz). The resulting baseband signal was then passed to a true-r.m.s. power meter.

The noise power measured by the r.m.s. power meter was calibrated using a known f.m. signal. A 1 kHz tone was used at 50mV peak-to-peak amplitude after C-MAC pre-emphasis,† with a modulation sensitivity of 13.5 MHz/V. (The video reference level is taken to be one volt peak-peak for a C-MAC signal).

The noise power was then measured when:

1. noise was introduced into an i.f. loop,
2. noise was introduced into an earth-station loop, after the TWTA,
3. noise was introduced into a transponder loop on the down-link,
4. noise was introduced into a transponder loop on the up-link.

For all these, noise was added at a level corresponding to 14 dB carrier-to-noise ratio in a 27 MHz bandwidth. The power levels in the system were such that a small amount of additional noise was inevitably introduced. The major additional source was the downconverter in the earth-station. The combined residual system noise was measured at the output of the downconverter using the offset-carrier technique and was found to be equivalent to a C/N of 26.6 dB.

The results of the down-link noise measurements are given in Table 2 and are compared there with theoretical values, including an allowance for residual system noise. There is good agreement between the values of S/N measured and those predicted from the carrier-to-noise ratio.

---

* OBO : output backoff – the amount the output level is reduced below saturated output power.

** IBO : input backoff – the amount the input power level is reduced below that required to produce saturation.

† according to curve E1 in Reference 1a.

TABLE 2 — Theoretical and measured unweighted signal-to-noise ratios for a down-link C/N of 14 dB.

Loop	Measured S/N (dB)	Theoretical S/N (dB)
I.F. loop	29.8	29.8
Earth-station loop	29.8	29.6
Transponder loop	29.4	29.6

The limits of experimental accuracy could account for the slight differences observed. Measurements of carrier power and noise power were each accurate to about ±0.1 dB. All differences between theory and measurement thus fall within the bounds of experimental accuracy. However, there is some doubt about the significance of the difference between the signal-to-noise ratios measured on the transponder loop and on the earth-station loop. (see below).

When noise was introduced before the earth-station, the measured unweighted signal-to-noise ratio for the transponder loop was 29.1 dB. When the same amount of noise was introduced on the down-link the S/N was 29.4 dB. There was thus a 0.3 dB additional degradation when the TWTs were included in the signal path.

3.1.2.2. Effect of a.m. to p.m. conversion

In a TWT, a.m. to p.m. conversion can cause extra phase-noise which degrades the signal-to-noise ratio after frequency demodulation. The theoretical degradation is given by:

$$\Delta\,(S/N) = 10 \log \left[1 + \left(\frac{K}{6.6}\right)^2\right] \text{ dB}$$

where Δ (S/N) is the degradation and K is the a.m. to p.m. conversion coefficient in degrees/dB. A degradation of 0.3 dB corresponds to a value of K of 1.8° /dB. The measured value of K for the TWT in the transponder was 1.3° /dB. The earth-station was run with 10 dB output back-off so it was operating virtually in the linear mode. However, there was still a residue of a.m. to p.m. conversion with the value for K being 0.5° /dB. If considered alone, this would cause negligible degradation. The TWT in the earth-station, being run in linear mode, introduces phase perturbations but does not modify the amplitude modulation. The saturated TWT in the satellite transponder therefore responds to the original amplitude modulation and produces further phase perturbations. As the phase perturbations in the two TWTs are caused by the same mechanism it is likely that they will be in the same direction and thus the effective value of K for the system will be the sum of the two individual components. The value of K for the whole system is thus the sum of the individual values of K for the earth-station and the satellite i.e. 1.8° /dB. This is in agreement with experiment, although the experimental accuracy is not ideal.

The degradation of signal-to-noise ratio by the phenomenon of a.m. to p.m. conversion was of particular interest. This effect has been predicted theoretically, but some of the measurements reported by other workers showed less degradation than predicted. One possible explanation is that the value of coefficient K is not a constant but a function of amplitude and frequency of the modulation. It was hoped to test this theory by measuring K as a function of amplitude and frequency and then comparing the results for degradation of S/N with predicted values. Two factors prevented this. First, the value of K was small and could not be measured with sufficient precision. Secondly, because K was small, the noise degradation was also small and hence it was difficult to distinguish between noise degradation and experimental inaccuracies. Two methods of measuring K were tried. The first used a microwave link analyser which measured only at a fixed frequency (278 kHz). The second used the two-tone test method and should have been capable of measurement with any wanted modulation frequency. However, with the analyser available and the system noise at a level which was small but not negligible, it was not possible to achieve sufficient accuracy to produce dependable results.

Also apparent discrepencies in the S/N values obtained for a given down-link C/N value, may arise because partial amplitude limiting of noise in an r.f. channel can increase the measured C/N slightly without affecting the S/N obtained from an f.m. demodulator. This problem was avoided in the measurements reported here.

3.1.2.3. Noise spectrum and effect of carrier-frequency offset

The results so far were obtained using a carrier at the centre-frequency of the pass-band. Fig. 2 shows the baseband noise spectrum of a demodulated 70 MHz carrier after de-emphasis (using C-MAC de-emphasis corresponding to pre-emphasis curve E1 specified in Reference 1a). This is compared with a theoretical curve derived using conventional theory. The two results are very similar except for a roll off at high frequencies caused by an 8.4 MHz video filter. There is thus good agreement with theory in this case.

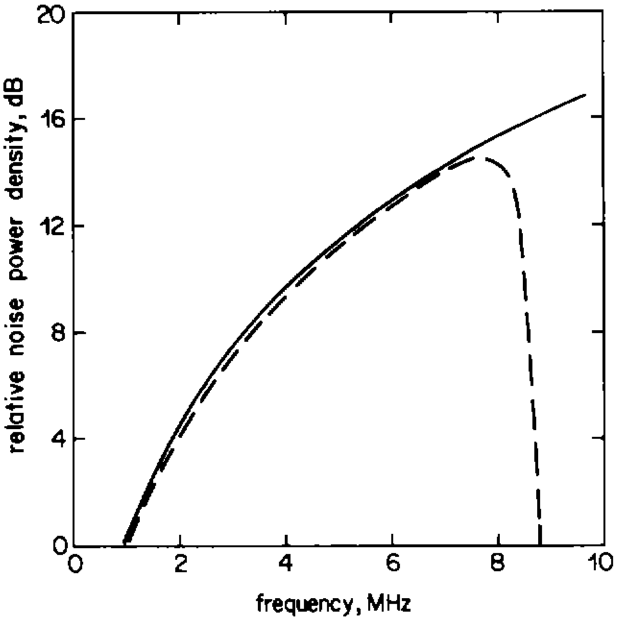

Fig. 2 — Baseband noise spectrum after demodulation.

——— theoretical curve.

— — measured curve.

When the carrier is not central, the spectrum of the demodulated baseband noise changes. Fig. 3 shows the baseband noise spectrum after demodulation of signals with carriers offset from the centre frequency by 0, 5 and 10 MHz. It is noticeable that the noise spectrum changes shape for carrier frequencies offset from channel centre and that the power in the video band (0 to 8.4 MHz) is lower for these offset carriers than for a central carrier. This effect is not predicted using the normal analysis.

The baseband noise spectrum is made up of two components, one from noise above the carrier frequency and one from noise below the carrier frequency. Both these are triangular but extend to the numerical difference between the carrier frequency and the edge of the i.f. band. The video noise spectrum observed is the sum (using power addition) of these two components Fig. 4 shows the theoretical results derived in this way. There is good agreement between the predicted and measured curves.

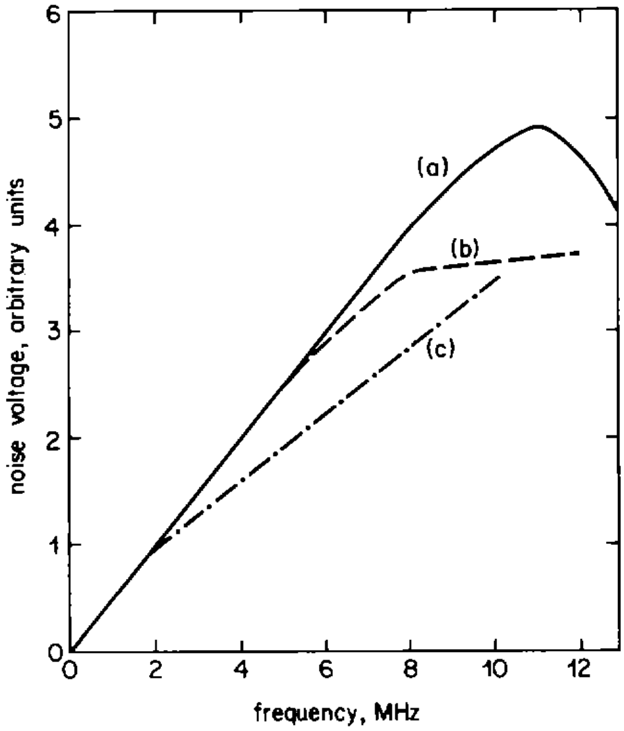

Fig. 3 — Measured baseband noise spectrum after demodulation.

——— central carrier.

— — carrier offset by 5 MHz.

—·— carrier offset by 10 MHz.

Thus the S/N ratio measured on demodulating an f.m. signal with an offset carrier will not necessarily be the same as that using a central carrier. Thus if S/N measurements are to be made in place of carrier-to-noise ratio measurements, a correction may have to be applied. This correction will depend on the precise offset of the carrier and on the i.f. filtering. If subjective noise-weighting is included, the difference will be reduced because low-frequency noise is usually unaffected. This effect has not been of concern until now because, in terrestrial f.m. microwave links for example, PAL systems are a.c. coupled, and the large amount of pre-emphasis keeps the carrier roughly central in the channel for the majority of signals.

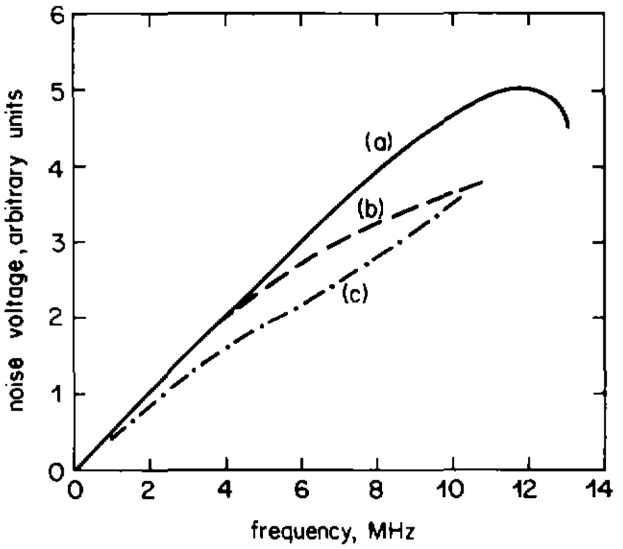

Fig. 4 – Predicted baseband noise spectrum after demodulation.

——— central carrier.

— — carrier offset by 5 MHz.

—·— carrier offset by 10 MHz.

However, C-MAC is d.c. coupled and uses less pre-emphasis. Thus a black or white level signal would be offset from the channel centre by about 4.8 MHz, giving a modified noise spectrum.

3.1.3. Video waveform measurements

Video waveform measurements were made using the MAC luminance channel. The waveforms used were the active-line portion of those normally used for PAL measurements but time compressed and with the full amplitude range of one volt used by MAC luminance.

Certain distortion measurements, such as differential phase and gain, were originally devised for composite video systems with a colour subcarrier and are not particularly relevant to C-MAC because there is no colour subcarrier. Instead the luminance distortion, as typified by the K-rating and the non-linearity, is more important. However, differential-phase distortion was included in the measurements to provide data for simulation studies.

A description of the standard waveform measurements is given in Ref. 6.

The measurments were made through:

1. the C-MAC Codec (luminance channel) alone,
2. the i.f. loop,
3. the earth-station loop,
4. the transponder loop.

The effect of different degrees of earth-station TWT saturation, and of added amplitude and group-delay slope, was also measured.

The results for the various loops operating normally (i.e. no distortion added, earth-station TWT saturated, and transponder TWT at 1 dB IBO) are given in Table 3.

The results of the modified loops are shown in Tables 4 to 8. Table 4 shows the effect of varying the output level of the earth-station TWT in the earth-station loop. Table 5 shows how amplitude and group-delay distortions affect the earth-station loop with a saturated TWT and Table Table 6 with a linear TWT. Table 7 shows the effect of amplitude and group-delay distortions in the transponder loop (saturated earth-station and transponder 1 dB IBO). Table 8 shows the effect of operating the transponder loop with either a linear or a saturated earth-station TWT. For some of the measurements only those parameters which appeared to change significantly were explored in depth; this explains the blanks in some of the tables.

In the early work on C-MAC there was no evidence that the commonly used luminance-type distortion measurements could be meaningfully applied to MAC. Neither was there much idea whether new types of distortions would be of interest.

As noted in Section 3.1.1 the picture quality remained good when transmitted through the complete system, even in the presence of a large amount of introduced distortion. The main effect of distortion was to give high-frequency loss in the video baseband. This is not critical at present, but would be if larger display screens become available, and particularly if an enhanced-resolution version of MAC were to be introduced to match the higher resolution capabilities of future displays.

The good picture-quality is reflected in the video waveform measurements. An overall K-rating of 3% corresponds[7] to an impairment which is perceptible but not annoying. Nearly all the K-ratings measured were less than 2%. Some did exceed 2% but not 3%. In these instances it was $K_{P/B}$ that was of concern. The corresponding

TABLE 3 — Video distortions : comparison of main loop configurations.

Measurement		Source	MAC codec	Earth-station loop (Saturated TWT)	Transponder loop (saturated earth-station, transponder 1 dB IBO)
K_{2T}	%	0.6	1.2	1.5	1.5
$K_{P/B}$	%	0.0	−1.7	−1.7	−2.0
K_B	%	0.3	−0.5	−0.5	0.0
K_{50}	%	0.0	0.0	0.0	0.0
Luminance Non-linearity	%	0.5	2.9	2.9	3.4
Differential gain distortion (line repetitive)	%	0.4	7.5	7.6*	13.5

TABLE 4 — Video distortions : Earth-station loop with varying degrees of TWT output back-off.

Measurement		Output back-off (dB)				
		0	1	3	5	10
K_{2T}	%	1.5	1.5	1.5	1.5	1.2
$K_{P/B}$	%	−1.7	−1.7	−1.7	−1.7	−1.7
K_B	%	−0.5				−0.5
K_{50}	%	0.0				0.0
Luminance non-linearity	%	2.9				2.7
Differential gain distortion (high APL)	%	6.8*	6.0	5.6	4.3	3.2

* The difference between the two results marked * is that in Table 3 a continuous waveform was used to measure differential-gain distortion. In Table 4 the average picture level has been changed by replacing the test waveform with white level three lines out of four.

TABLE 5 – Video distortions : earth-station loop with amplitude and group-delay distortions : saturated TWT.

Measurement		Type of Distortion							
		None	Linear		Parabolic				Combined
			Amplitude	Group delay	Amplitude (dB/MHz^2)			Group delay	0.3 dB/MHz 0.6 ns/MHz 0.045 dB/MHz^2 0.2 ns/MHz^2
			0.3 dB/MHz	0.6 ns/MHz	0.015	0.03	0.045	0.2ns/MHz^2	
K_{2T}	%	1.5	1.5	1.5			1.5	1.5	1.4
$K_{P/B}$	%	−1.7	−1.7	−1.7	−2.0	−2.8	−2.3	−1.6	1.3
K_{BAR}	%	−0.5	−0.5	−0.0			−0.5	−0.8	−0.5
K_{50}	%	0.0	0.0	−0.0			0.0	0.0	0.0
Luminance non-linearity	%	2.9	3.0	3.1			3.2	3.1	2.9
Differential gain distortion	%	6.8	5.9	15.8			9.8	15.8	68.1

TABLE 6 — Video distortions : earth-station loop with amplitude and group-delay distortions : linear TWT.

Measurement		Type of Distortion				
			Parabolic amplitude dB/MHz^2			Combined
		None	0.015	0.03	0.045	0.3 dB/MHz 0.6 ns/MHz 0.045 dB/MHz^2 0.2 ns/MHz^2
K_{2T}	%	1.2				1.7
$K_{P/B}$	%	−1.7	−1.7	−1.7	−2.0	−1.0
K_{BAR}	%	−0.5				−0.8
K_{50}	%	0.0				0.0
Luminance non-linearity	%	2.9				2.4
Differential gain distortion	%	7.6				40.3

TABLE 7 — Video distortions : transponder loop with amplitude and group-delay distortions : earth-station TWT saturated.

Measurement		Distortion						
			Linear		Parabolic			
		None	Amplitude (dB/MHz)	Group delay (ns/MHz)	Amplitude (dB/MHz^2)			Group delay (ns/MHz^2)
			0.3	0.6	0.015	0.03	0.045	0.2
K_{2T}	%	1.5	1.5	1.5	1.5	1.2	1.5	1.5
$K_{P/B}$	%	−2.0	−1.7	−2.0	−2.0	−2.7	−2.7	−1.3
K_B	%	0.0	−0.5	−0.5	−0.5	−0.5	−0.8	0.5
K_{50}	%	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Luminance non-linearity	%	3.4	3.1	3.1	3.4	3.4	3.3	2.8
Differential gain distortion	%	13.5	12 4	15.8	14.1	13.6	13.4	14.5

TABLE 8 – Effect of operating the transponder loop with a linear or saturated TWT in the earth-station.

Measurement		Earth station output back-off (dB)	
		0 (saturated)	10 (linear)
K_{2T}	%	1.5	1.5
$K_{P/B}$	%	–2.0	–1.7
K_B	%	0.0	–0.5
K_{50}	%	0.0	
Luminance non-linearity	%	3.4	3.0
Differential gain distortion	%	13.5	12.0

subjective effect appeared to be a drop in the high-frequency response. There was no increase in ringing on edges observed in the subjective tests. It is important to realise that the main source of degradation observed in these tests was the C-MAC codec itself. The transponder rarely introduced additional degradation of K-ratings of more than 0.5%. Similar comments apply to luminance non-linearity; the transponder never degraded the signal by more than 0.5%.

The figures for differential-gain distortion demonstrate the need for pre-emphasis in subcarrier-based systems. The C-MAC pre-emphasis curve is designed to reduce noise and sensitivity to adjacent-channel interference, and gives much less low-frequency attenuation than that for PAL. As a result the differential gain distortion is much higher. Fortunately this has little visible effect on a C-MAC picture.

3.1.4. Baseband amplitude/frequency response

The baseband amplitude/frequency response was measured. This was accomplished by adding a slow frequency sweep (over several seconds) at low level to the luminance input of the MAC coder. The mean level of the luminance signal was black level. The received sweep was processed by a network analyser.

As with the waveform measurements the amplitude/frequency response was measured for:

1. I.f. loop,
2. The earth-station loop,
3. The transponder loop.

Again the effects of different degress of TWT saturation and amplitude and group-delay slope were also measured.

Fig. 5 shows the baseband amplitude/frequency responses for the i.f. and transponder loops operating normally.

Fig. 6 shows the baseband amplitude/frequency responses for i.f. loop, the earth-station loop and the transponder loop in the presence of distortion.

Figs. 7 & 8 show the baseband amplitude/frequency response for the transponder loop with various i.f. amplitude and group-delay perturbations.

The amplitude/frequency response curves show that high-frequency loss is a potential problem. However, the curves measured here are probably the worst case. In this experiment the response was measured using the quiescent black-level picture. The r.f. spectrum is therefore biased very much towards the edge of the channel where it is very much more sensitive to the introduced degradations. These degradations are usually small when the signal is central in the channel but increase as the signal moves towards the edge. This

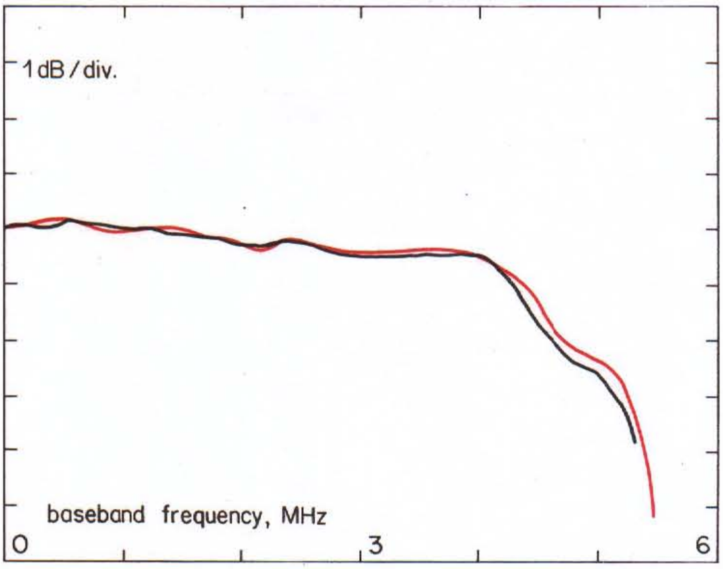

Fig. 5 – Baseband amplitude-frequency response through undistorted system.

— i.f. loop.

— transponder loop.

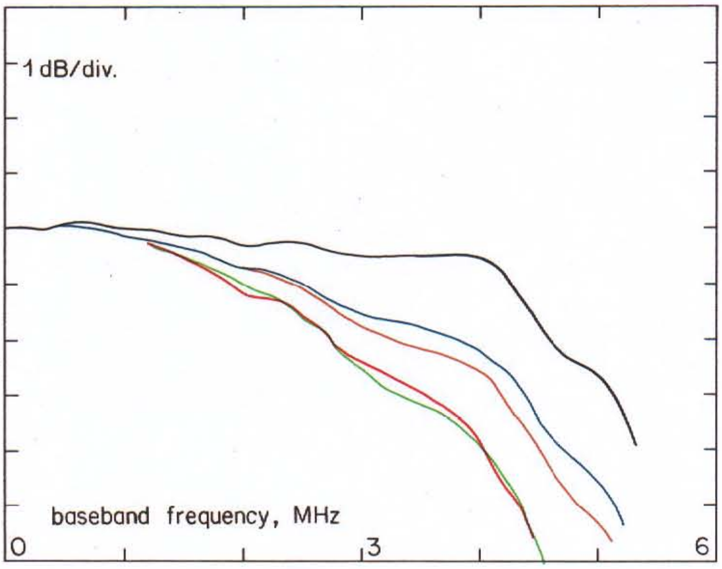

Fig. 6 – Baseband amplitude-frequency response : effect of saturated TWT

— i.f. loop : undistorted.

— i.f. loop : gross distortion.

— earth-station loop : gross distortions with linear TWT.

— earth-station loop : gross distortions with saturated TWT.

— transponder loop : gross distortions with saturated earth-station TWT and transponder TWT at 1 dB IBO.

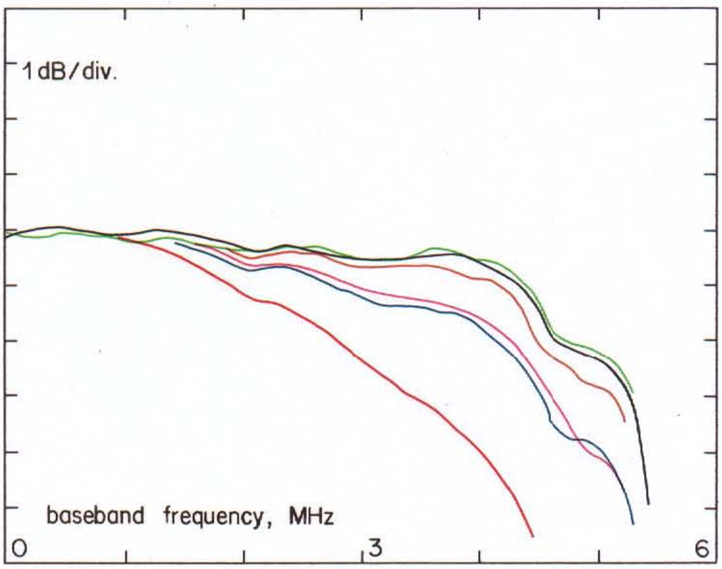

Fig. 7 – Baseband amplitude-frequency response : transponder loop with distortion

— no distortion.

— 0.3 dB/MHz.

— 0.045 dB/MHz^2.

— 0.6ns/MHz.

— 0.2ns/MHz^2.

— all distortions simultaneously.

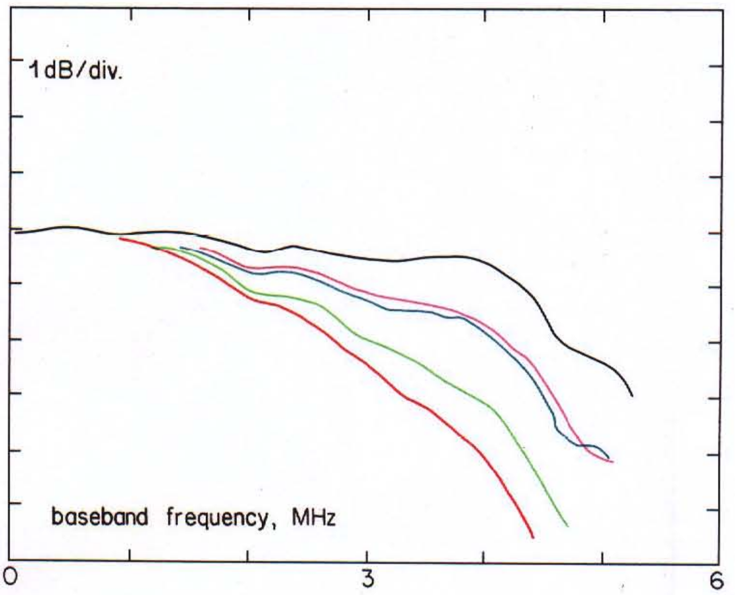

Fig. 8 – Baseband amplitude-frequency response : transponder loop with distortion.

bias, and the spectral truncation involved with high modulation frequencies, explains the poor h.f. response observed. We should expect better performance at grey level, for instance. Figs. 7 and 8 show that the response curves appear to be more sensitive to parabolic than to linear distortions, possibly because of non-linear effects in the TWTs removing some of the linear distortions, but this would need to be confirmed by a detailed analysis or simulation.

3.2. Data tests

Phase-shift keying of the 2-4 PSK type[2] is used for the transmission of data in C-MAC. The data rate is 20.25 Mbit/s during the data burst. Two properties of 2-4 PSK are of interest:

1. its spectrum,
2. its sensitivity to noise and distortion.

The first property is important for regulatory reasons; the second for performance. The r.f. channel influences both.

3.2.1. The spectrum of 2-4 PSK

The spectrum of 2-4 PSK was measured using a C-MAC modulator with a pseudo-random binary sequence input to the data channel, and unmodulated carrier during the vision time-slot. It was measured at

1. the modulator output,
2. the earth-station output,
3. the transponder output.

The effects of filtering and saturation were measured by adding extra source filters at the output of the C-MAC coder and by modifying the amount of back-off of the earth-station TWT and transponder TWT.

The spectrum at the output of the modulator is given in Fig. 9, at the output of the earth-station in Figs. 10 to 13 and at the output of the transponder in Figs. 14 to 16. Selected fractional out-of-band power curves are shown in Figs. 17 and 18 for the earth-station and satellite transponder respectively.

The spectrum of 2-4 PSK depends on the data being transmitted. However, for DBS there will be two data scrambling processes applied, one for energy dispersal and one for encryption. Therefore the spectra obtained here using a pseudo-random binary sequence are typical. Unfiltered 2-4 PSK has a spectrum:

$$H(f) = \frac{\Upsilon \sin 2\pi(f-f_o)\Upsilon}{2\pi(f-f_o)\Upsilon} \qquad (1)$$

--- where $\frac{1}{\Upsilon} = 20.25 \times 10^6$ Hz

f_o is the channel centre frequency

f is the frequency

In practice filtering will always be applied. In the C-MAC equipment used here, a 38 MHz wide

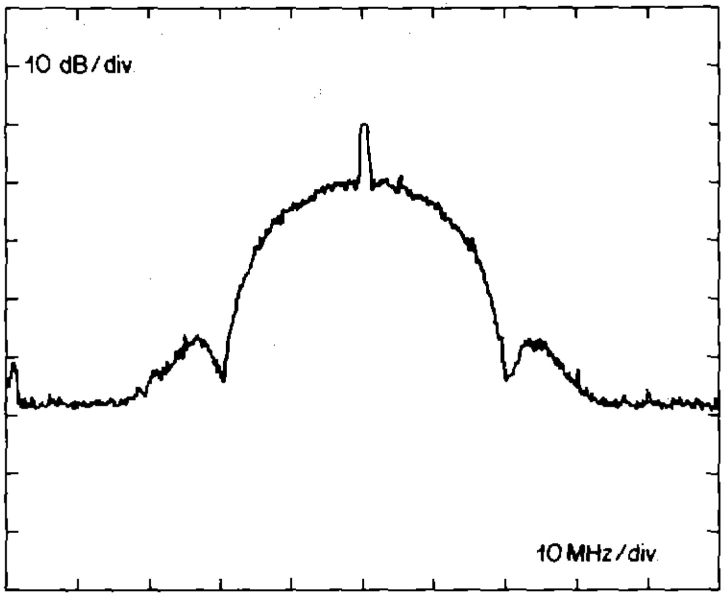

Fig. 9 – 2-4 PSK spectrum at the output of the modulator.

filter used, giving the spectrum shown in Fig. 9. The main features are:

(a) a broad main lobe,

(b) a null at ±20.25 MHz,

(c) an attenuated sidelobe.

The spike at centre frequency is due to the unmodulated vision carrier.

When this signal is filtered and then amplified in the earth-station, the resultant spectra (Figs. 10 to 13) show variations on the three main features:

(a) The shape of the main lobe is determined largely by the filtering applied to the signal. For a given transmitted power, a narrower main lobe usually results in a higher power spectral density (p.s.d.) near the carrier frequency.

(b) The sidelobes are re-generated to an extent which is dependent on the filtering and the degree of saturation of the TWT.

(c) The position of the first minimum depends on filtering and saturation.

The same spectral re-generation features can be seen in the output of the transponder (Fig. 14), although not all these curves are important, since the transponder is usually run at or close to saturation for efficiency. Thus the output spectrum is usually dominated by the degree of saturation of the TWT in the satellite transponder, as is shown in Figs. 15 and 16. These show that the OMUX filter can contribute to the sidelobe suppression too. The asymmetry in the sidelobes is caused by a slight offset in the centre frequency of the OMUX with respect to the nominal channel. The OMUX is operating at a slightly lower frequency than optimum. As a result, the upper sidelobes of the spectrum are attenuated more than the lower ones. The main lobe appears to be shaped mainly by the filtering applied to the feeder link.

Figs. 17 and 18 show the fractional out-of-band power for selected cases. They show that adjacent channel interference may be difficult to remove because of the overlapping of the DBS channels*. There is potential for reduction of interference in the next-but-one channel either by increasing the back-off of the amplifier (most useful for the earth-station), or by filtering the output (most useful in the satellite).

The unfiltered spectrum of 2-4 PSK predicted by equation 1 is only valid for a perfect 2-4 PSK signal. It is not possible to generate closed form expressions for the spectrum of a normal transmission channel. Instead the spectrum is usually predicted by a computer simulation. All the features of a real transmission channel may in theory be included in a simulation.

The prediction of equation 1 shows a reasonable agreement with the experimental results, but of course does not predict the fine variations in results as the system parameters are

---

*The channel spacing in ITU Regions 1 and 3 is 19.18 MHz for DBS in the 12 GHz band.

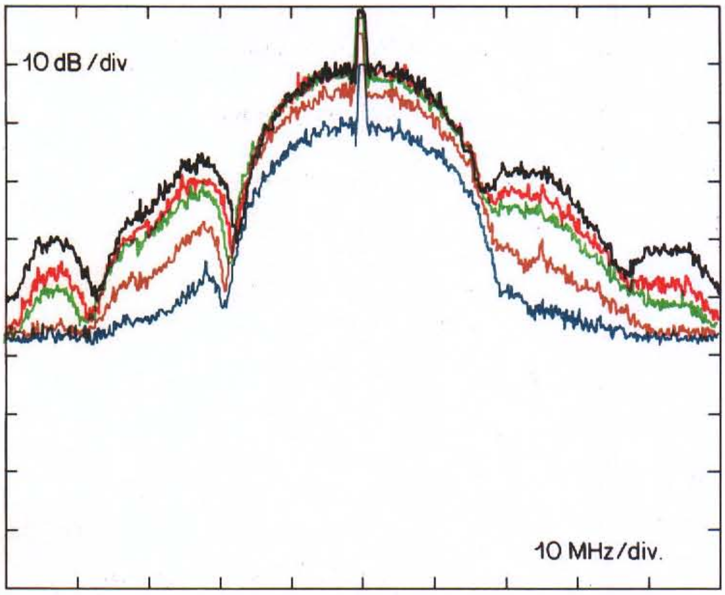

Fig. 10 – 2-4 PSK spectrum at the output of the earth-station : Source filter 38 MHz.

— saturated TWT.

— 1 dB output back-off.

— 2 dB output back-off.

— 5 dB output back-off.

— 10 dB output back-off.

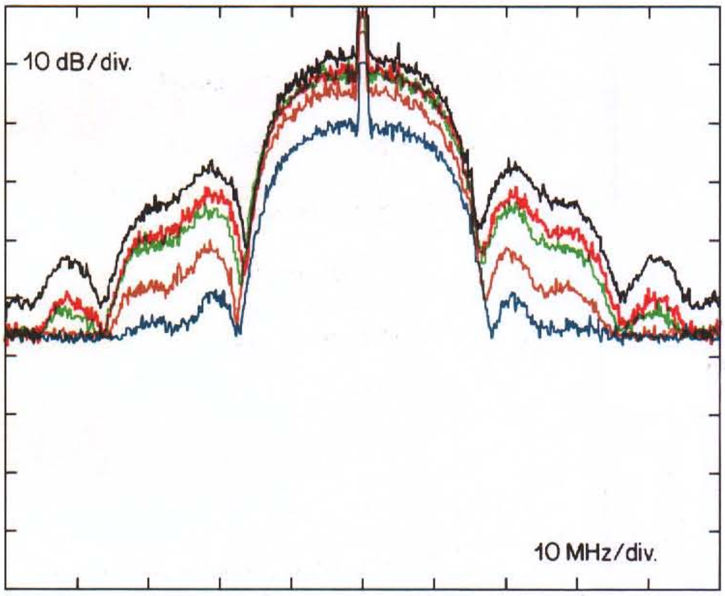

Fig. 11 – 2-4 PSK spectrum at the output of the earth-station : Source filter 27 MHz.

— saturated TWT.

— 1 dB output back-off.

— 2 dB output back-off.

— 5 dB output back-off.

— 10 dB output back-off.

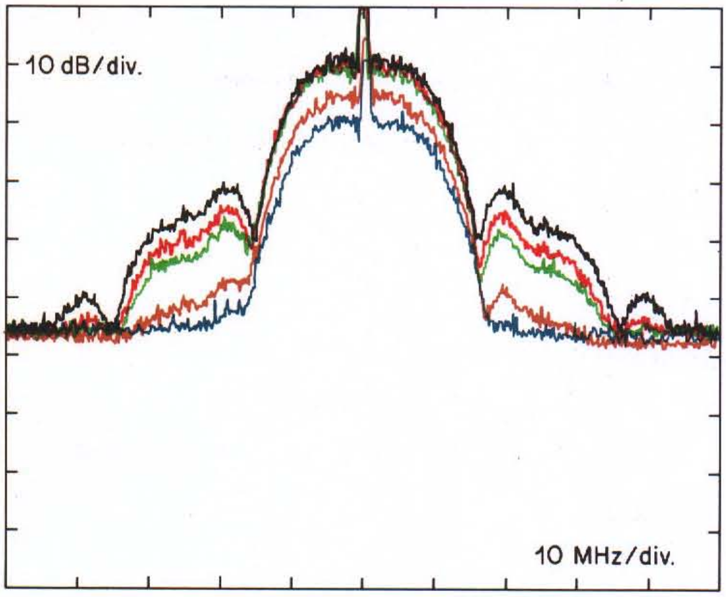

Fig. 12 – 2-4 PSK spectrum at the output of the earth-station. Source filter 21 MHz.

— saturated TWT.

— 1 dB output back-off.

— 2 dB output back-off.

— 5 dB output back-off.

— 10 dB output back-off.

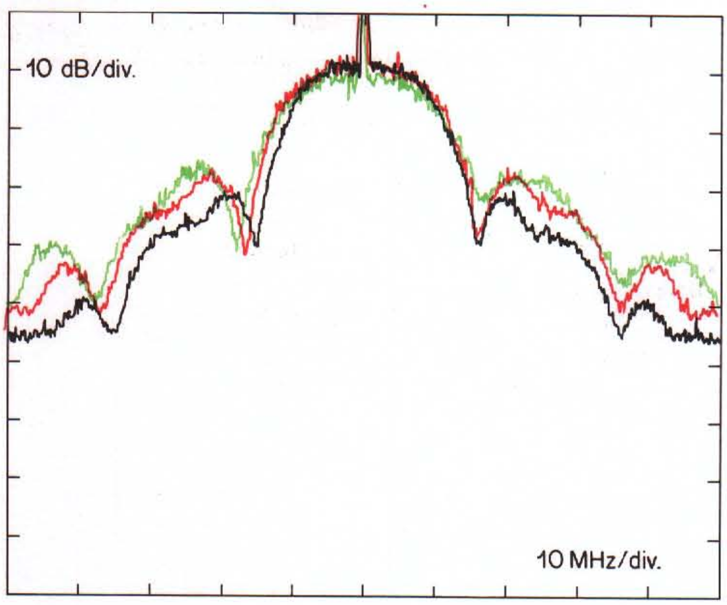

Fig. 13 – 2-4 PSK spectrum at the output of the earth-station. Saturated TWT.

—— 38 MHz source filter.

—— 27 MHz source filter.

—— 21 MHz source filter.

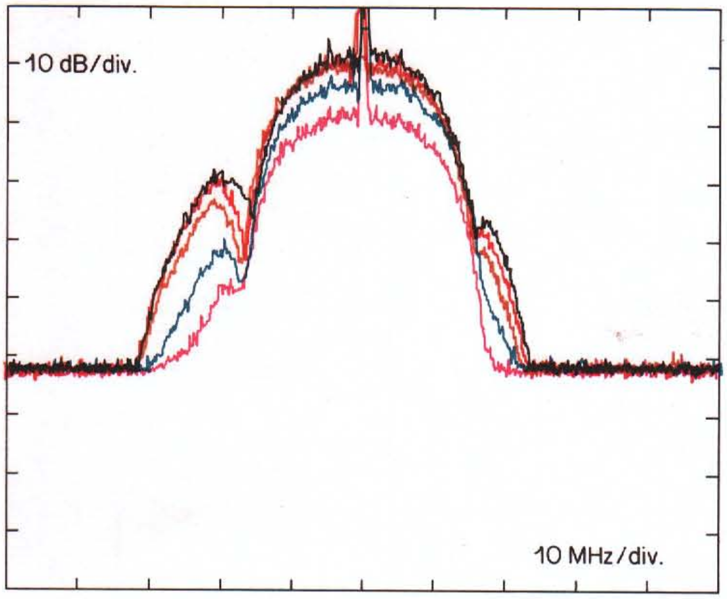

Fig. 14 – 2-4 PSK spectrum at output of transponder (linear earth-station) : Source filter 27 MHz.

—— transponder TWT saturated.

—— 1 dB input back-off.

—— 5 dB input back-off.

—— 10 dB input back-off.

—— 15 dB input back-off.

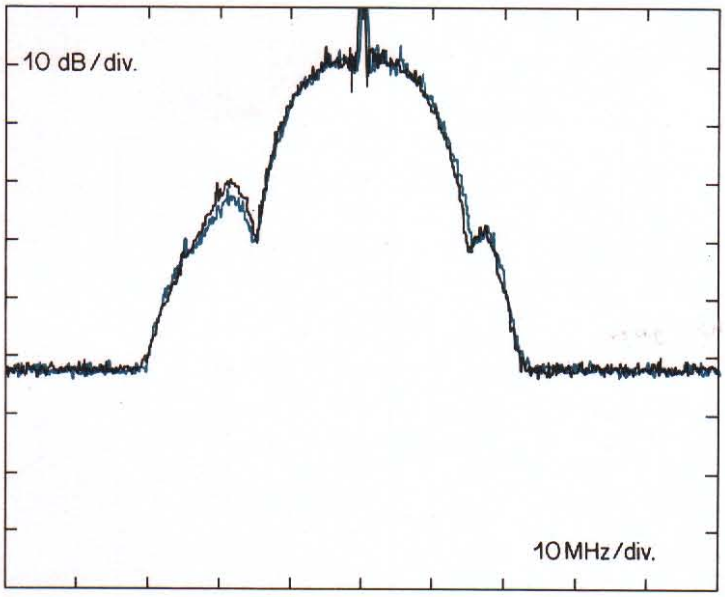

Fig. 15 – 2-4 PSK spectrum at output of transponder (TWT 1 dB input back-off) : Source filter 21 MHz.

—— earth-station saturated.

—— earth-station 10 dB output back-off.

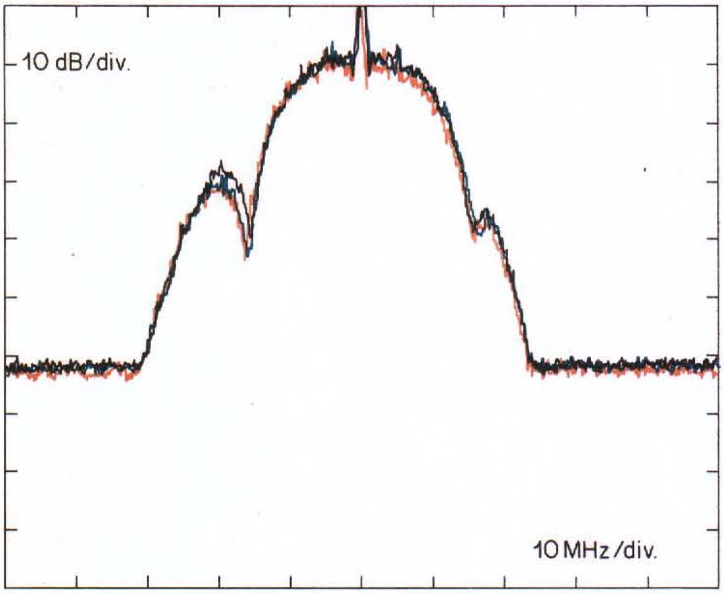

Fig. 16 – 2-4 PSK spectrum at output of transponder (TWT 1 dB input back-off) : Source filter 27 MHz.

——— earth-station saturated.

——— earth-station 5 dB output back-off.

——— earth-station 10 dB output back-off.

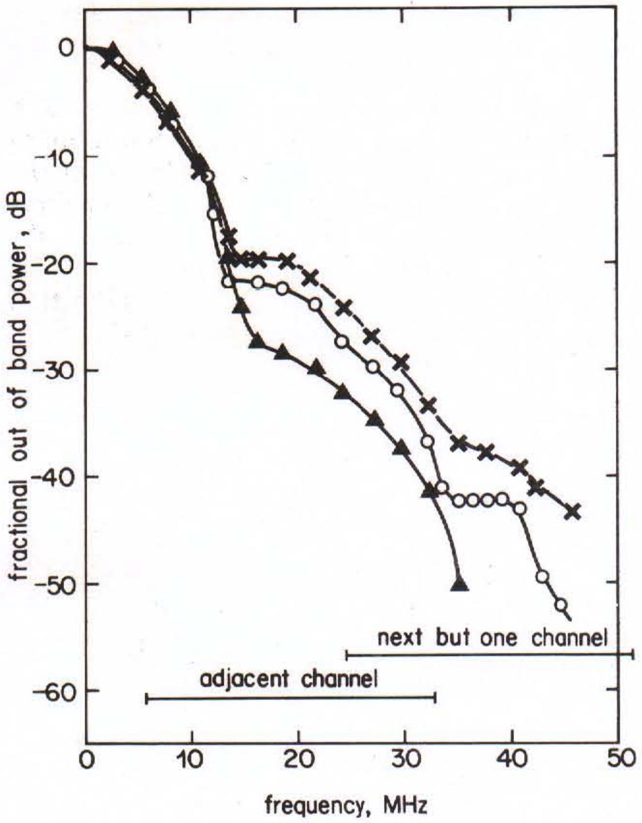

Fig. 17 — 2-4 PSK fractional out-of-band power from earth-station: Source filter 27 MHz.

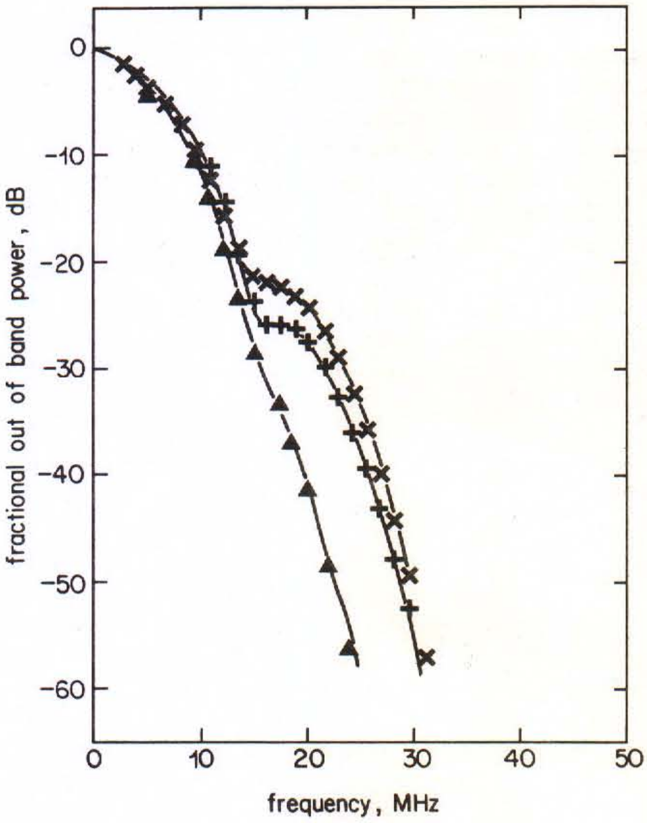

Fig. 18 — 2-4 PSK fractional out-of-band power from transponder: Source filter 27 MHz, earth-station saturated.

—✕— earth-station TWT saturated.

—○— 1 dB output back-off.

—▲— 5 dB output back-off.

—✕— transponder saturated, lower sidebands.

—+— transponder saturated, upper sidebands.

—▲— transponder 5 dB input back-off.

varied. For example, it is not possible to predict the sidelobe regeneration in the 2-4 PSK spectrum. Thus, this analysis of the system is useful to understand how the system works, but in order to determine what operational limits may be needed, a more detailed analysis must be used. Ideally, the system could be modelled by computer simulation and provided that the entire system is completely and accurately modelled, the results of the simulation and the experiment should be identical.

At the time of writing, no results based on a complete model of the system used in these tests are available. However, some spectra have been predicted by computer. The spectral simulations of 2-4 PSK show good agreement with measured results. Figs. 19, 20 and 21 show the computer predictions for the spectrum of 2-4 PSK if the signal is subject only to filtering and amplitude non-linearities as measured for the earth-station TWT. There is a good match between these and Figs. 10, 11 and 12. However, there were minor differences, which were thought might be caused by a.m. to p.m. conversion, (but it was not possible to verify this assertion because of the limited accuracy of the available measurements). In order to appreciate the type of effect, an a.m. to p.m. degradation equivalent to 3.9°/dB at its peak was arbitrarily introduced. The new predicted spectrum is seen in Figs. 22, 23 and 24. The new spectrum shows some additional features observed in the experiment, but the level of regenerated sidelobes is not in as good agreement as for the case with no a.m. to p.m. conversion.

The measured level of regenerated sidelobes of the 2-4 PSK spectrum did not agree precisely with predictions made by the EBU, probably because of differences between the actual TWT used in these experiments and the model used for their simulation. In particular, the actual regeneration was higher than expected. Thus some back-off of the earth-station TWT may be required to comply with the C-MAC specification [1a] for the out-of-band radiated power. (It is also thought that similar problems may be encountered if klystrons are used in place of the TWTs at the earth-station).

3.2.2. Error performance of the data channel

The error performance of the data channel is usually characterised by the bit error ratio (BER) which is the ratio of incorrectly received binary digits to the total transmitted. This is a strong function of the carrier-to-noise ratio and (hopefully) a weak function of the specific channel implementation.

3.2.2.1. BER of the unimpaired signal

The bit error ratio was measured as a function of carrier-to-noise ratio for

1. i.f. loop,
2. earth-station loop,
3. transponder loop.

The transponder TWT was always close to saturation (1 dB IBO), but the earth-station TWT was backed-off by 10 dB at the output for some tests. The source filtering was not modified (38 MHz in all cases). The results are shown in Figs. 25, 26 and 27.

Fig. 25 shows the relationship observed between single and double errors, using an i.f. loop. This demonstrates the high probability of a double error caused by differential demodulation.

Fig. 26 shows the variation of BER with C/N for i.f., earth-station and transponder loops with the earth-station running in linear mode. There is very little variation between the three cases and a single curve is shown to represent the measured results. The performance of the i.f. loop is about 1.1 dB worse than the theoretical curve for differentially-demodulated 2-4 PSK, based on the formula:

$$\mathrm{BER} = \tfrac{1}{2} e^{-1.33\, C/N} \qquad (3)$$

(Note that C/N is measured in a bandwidth of 27 MHz although the bit rate is 20.25 Mbit/s). The BER improves when the transmission chain is introduced, usually by less than 0.2 dB equivalent C/N improvement. As the measurement accuracy is about 0.1 dB some or all of this improvement may be fictitious.

Fig. 27 shows the variation of BER for i.f., earth-station and transponder loops with the earth-station saturated. The results are similar to those of Fig. 26 where the earth-station was run in a linear mode, but this time the variation between the different loops is greater.

The 1 dB difference between the theoretical and measured BER of the 2-4 PSK is partly a function of the measurement system. The carrier level was measured using an unmodulated carrier. When modulated, there is a noticeable amount of energy which falls outside the 38 MHz transmit

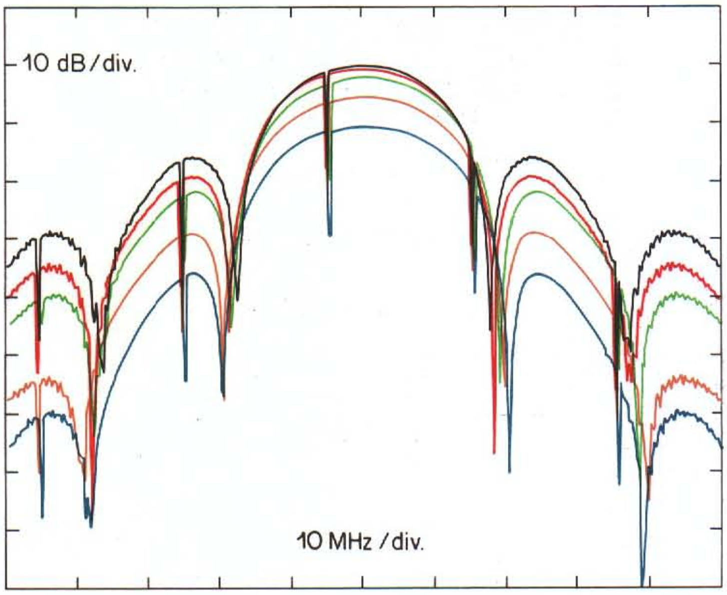

Fig. 19 – Simulated 2-4 PSK spectrum at the output of the earth-station: No a.m./p.m. conversion, source filter 38 MHz.

—— saturated TWT

—— 1 dB output back-off.

—— 2 dB output back-off.

—— 5 dB output back-off.

—— 10 dB output back-off.

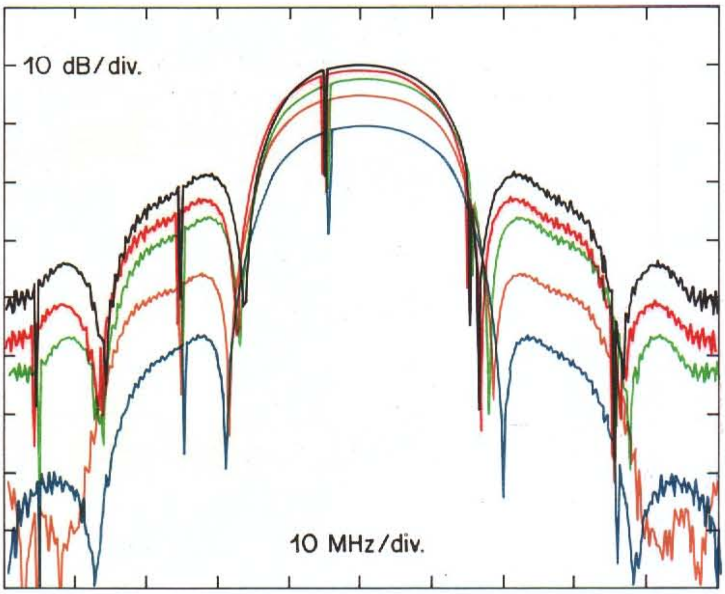

Fig. 20 – Simulated 2-4 PSK spectrum at the output of the earth-station: No a.m./p.m. conversion, source filter 27 MHz.

—— saturated TWT.

—— 1 dB output back-off.

—— 2 dB output back-off.

—— 5 dB output back-off.

—— 10 dB output back-off.

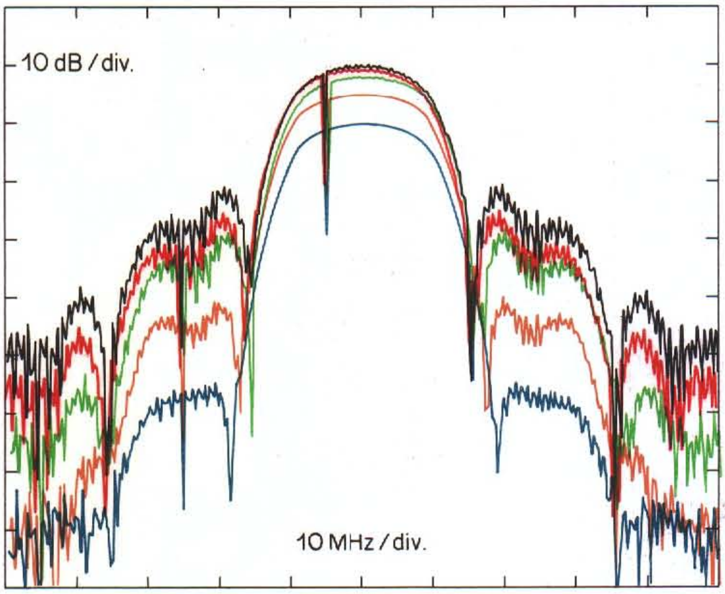

Fig. 21 – Simulated 2-4 PSK spectrum at the output of the earth-station: No a.m./p.m. conversion, source filter 21 MHz.

—— saturated TWT.

—— 1 dB output back-off.

—— 2 dB output back-off.

—— 5 dB output back-off.

—— 10 dB output back-off.

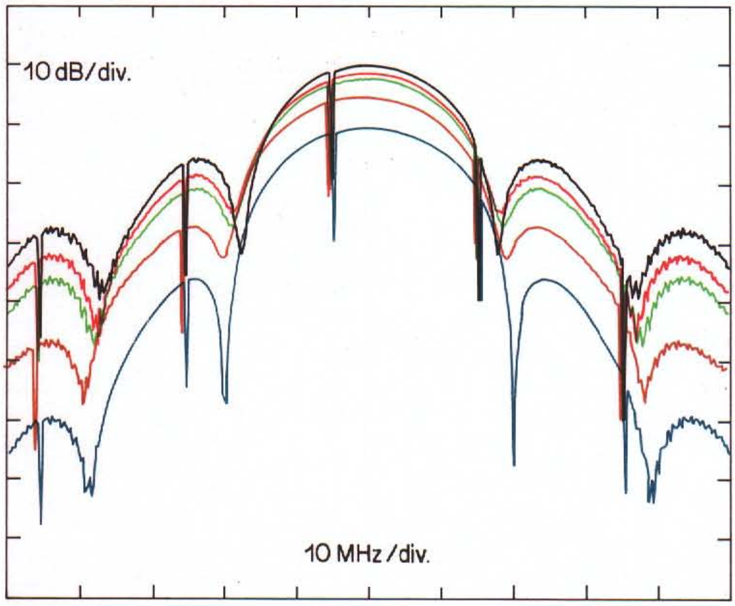

Fig. 22 – Simulated 2-4 PSK spectrum at the output of the earth-station: Notional a.m./p.m. conversion included, source filter 38 MHz.

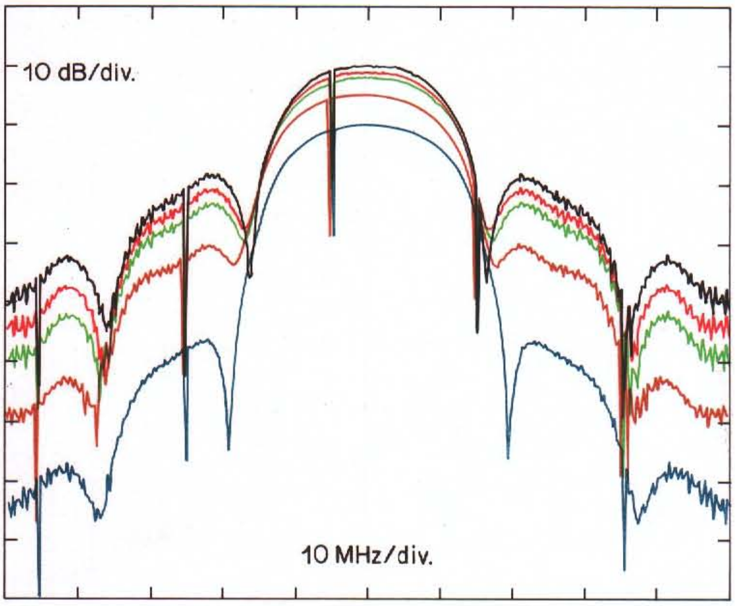

Fig. 23 – Simulated 2-4 PSK spectrum at the output of the earth-station: Notional a.m./p.m. conversion included, source filter 27 MHz.

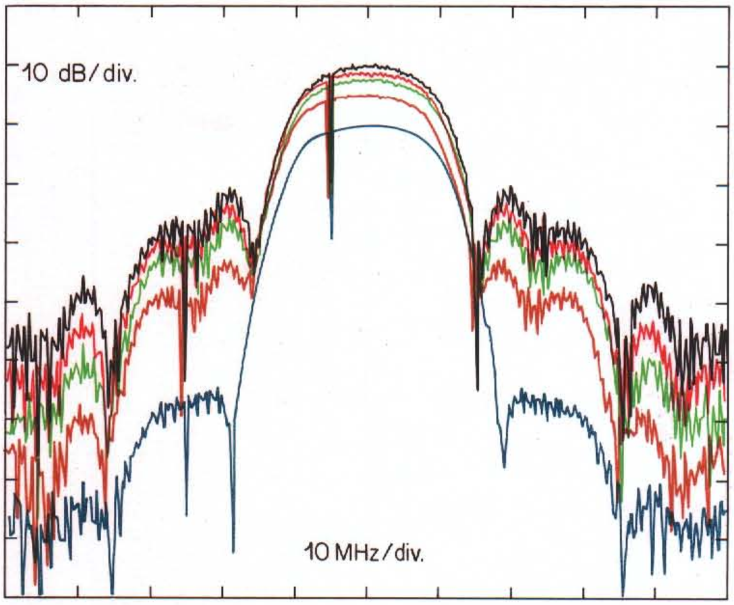

Fig. 24 – Simulated 2-4 PSK spectrum at the output of the earth-station: Notional a.m./p.m. conversion included, source filter 21 MHz.

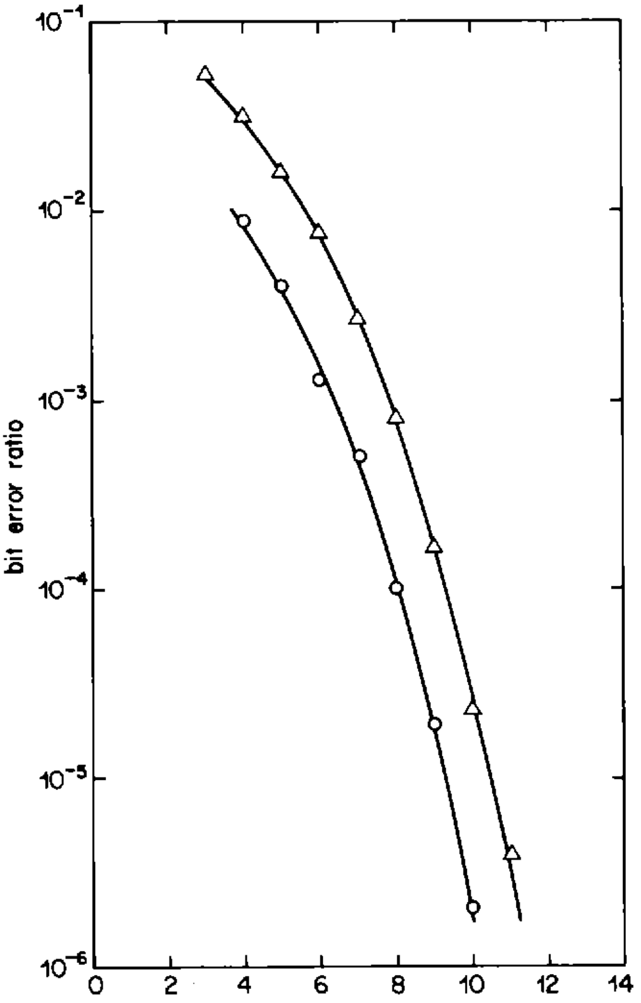

Fig. 25 — 2-4 PSK bit error ratio as a function of C/N for i.f. loop.

filter. Thus the actual transmitted power is less than that measured. In addition, the 21 MHz receiver filter is not perfectly matched to the transmitted spectrum. The discrepancy predicted by computer simulations of a linear system is about 0.5 dB due to 38 MHz transmit filtering and 0.1 dB for the receiver filter.

3.2.2.2. BER of signals with deliberate distortion

In order to investigate the effect of channel imperfections, distortion was added at the output of the C-MAC coder. Noise was then added at the C-MAC decoder until the BER was 10^{-3}.

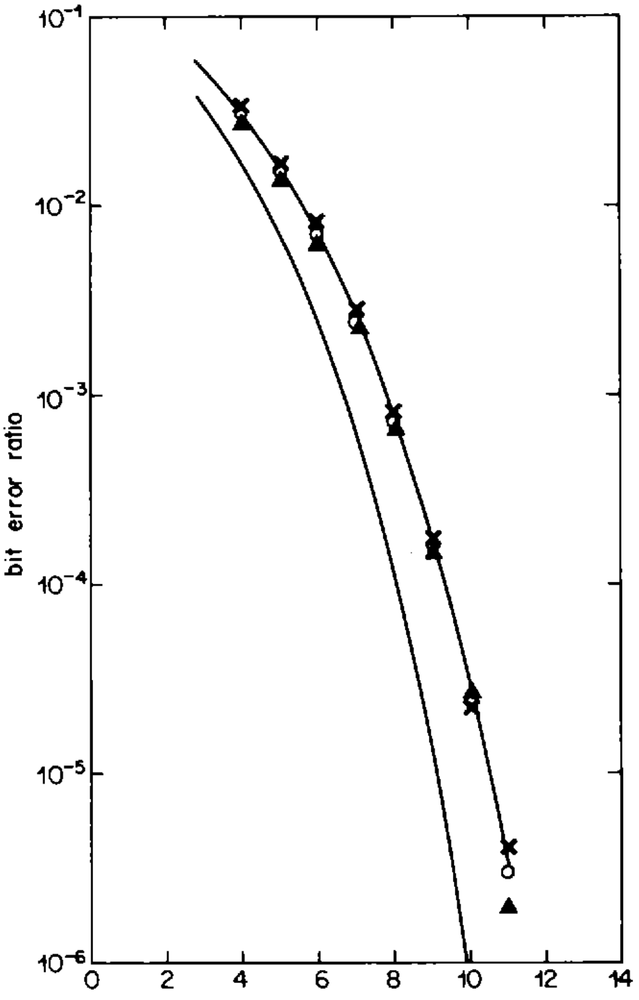

Fig. 26 — 2-4 PSK bit error ratio as a function of C/N; linear earth-station.

Figs. 28 to 31 show the effect of introduced distortion. The distortion unit itself introduced some variation in gain as the impairments were changed. This has been allowed for in curves for the i.f. loop. However, it is less easy to choose a valid correction factor when a saturated TWT is involved. As the tendency will be towards removing any amplitude fluctuations, no correction was applied in these cases. There will be little residual error when both TWTAs are in series, but the results for the earth-station loop may benefit from a close study of the errors involved. The transfer characteristics of the earth-station and transponder TWTs, Figs. 32 and 33 respectively, show that the effect is small for an input back-off less than 1 dB. Only linear amplitude distortion exceeded this value.

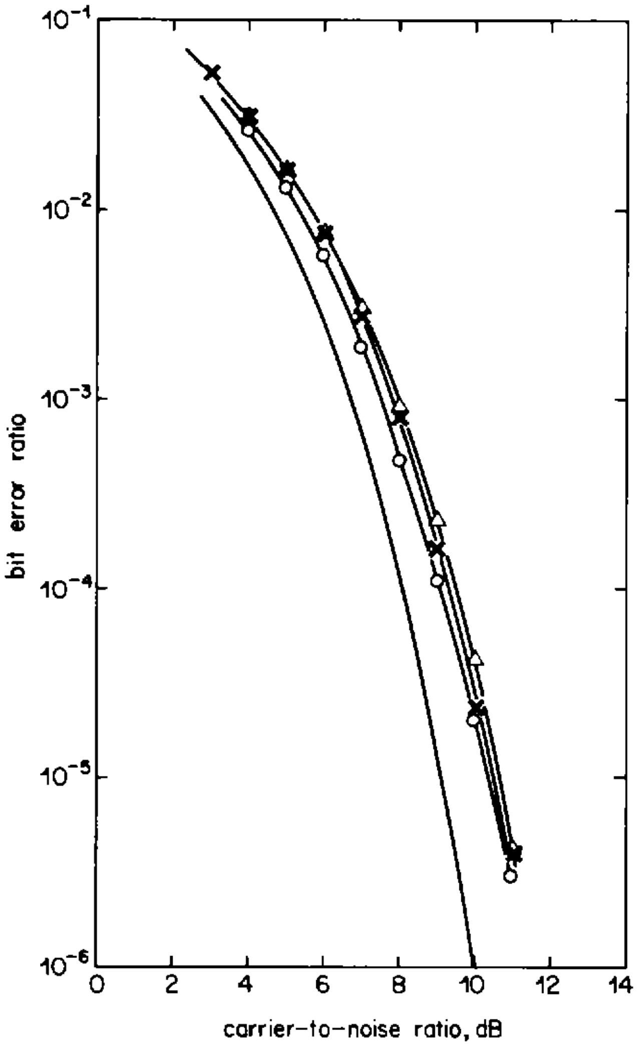

Fig. 27 — 2-4 PSK bit error ratio as a function of C/N; saturated earth-station.

— $P_e = \frac{1}{2}e^{-1.33\ C/N}$

—✕— i.f. loop.

—○— earth-station loop, saturated.

—△— transponder loop (transponder 1 dB input back-off, earth-station saturated).

Fig. 28 shows the effect of linear amplitude distortion. The i.f. loop shows a small amount of degradation. This is largely removed by two TWTs in series, which appear to be removing most of the extra amplitude modulation. It does not appear to be removed in the earth-station loop, however. The explanation may be that the insertion loss of the distortion unit for linear amplitude distortion takes an extreme value (1.85 dB loss). Although the earth-station is saturated, a 1.85 dB input back-off could result in a small output back-off and hence a reduction in C/N and consequent increase in degradation.

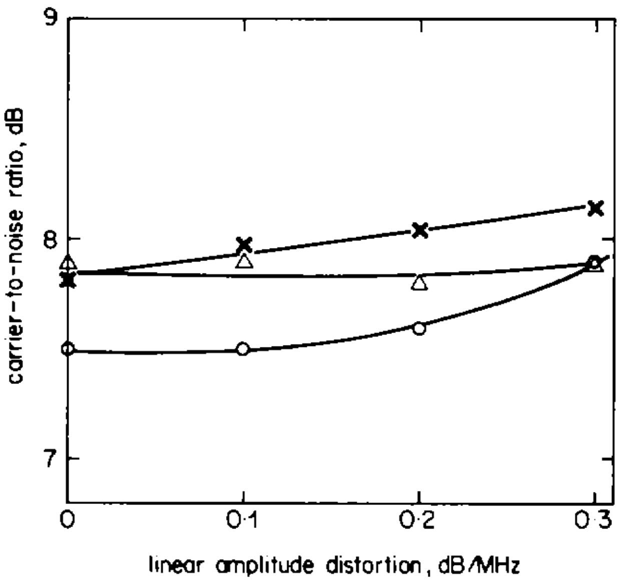

Fig. 28 — 2-4 PSK C/N required to achieve a bit error ratio of 10^{-3} in the presence of linear amplitude distortion.

—✕— i.f. loop.

—○— earth-station loop (saturated).

—△— transponder loop (transponder 1 dB input back-off, earth-station saturated).

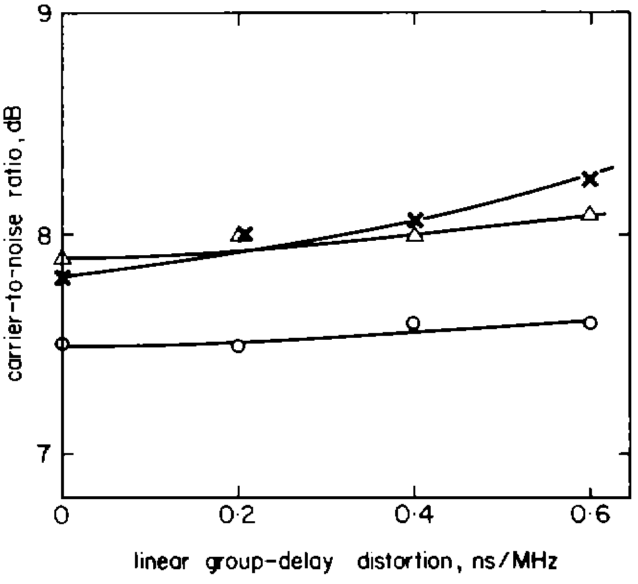

Fig. 29 — 2-4 PSK C/N required to achieve a bit error ratio of 10^{-3} in the presence of linear group-delay distortion.

—✕— i.f. loop.

—○— earth-station loop (saturated).

—△— transponder loop (transponder 1 dB input back-off earth-station saturated).

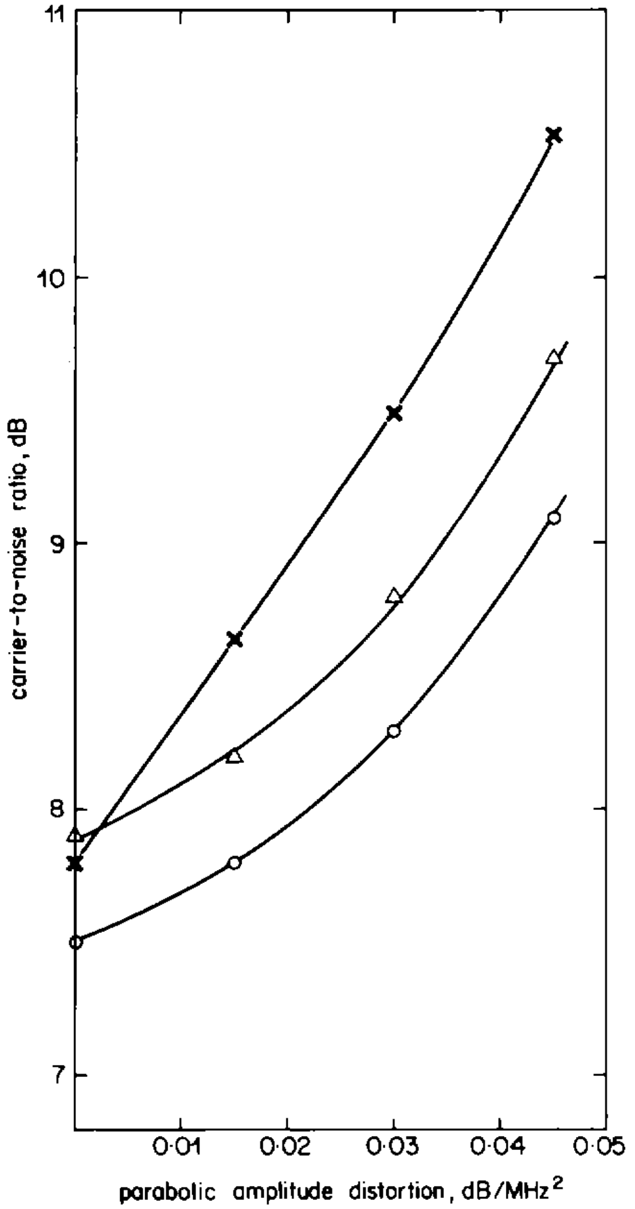

Fig. 30 — 2-4 PSK C/N required to achieve a bit error ratio of 10^{-3} in the presence of parabolic amplitude distortion.

—✕— i.f. loop.

—○— earth-station loop (saturated).

—△— transponder loop (transponder 1 dB input back-off, earth-station saturated).

Fig. 29 shows the effect of linear group-delay distortion. This type of distortion can lead to amplitude perturbations and so there will be some improvement in performance after passing through a saturated TWT. This is reflected in the curves for the earth-station and transponder loops.

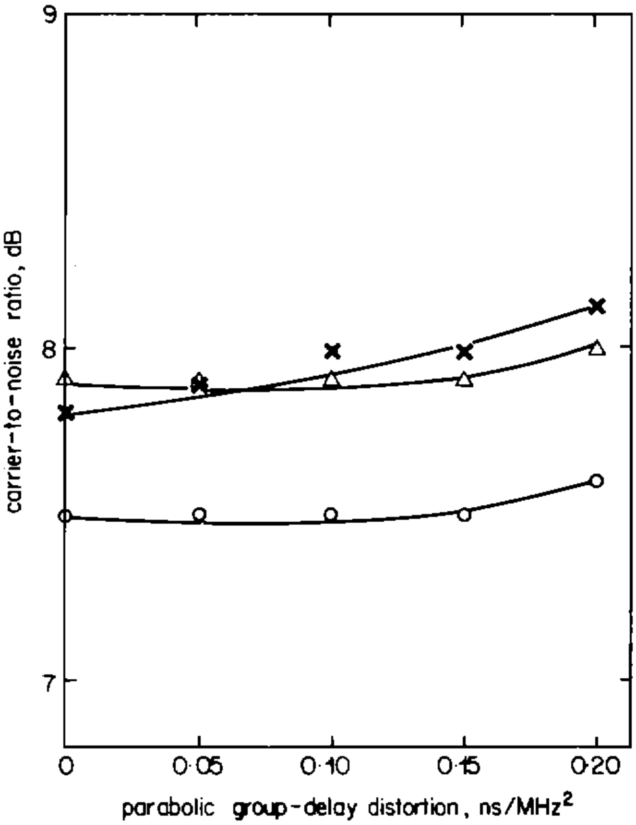

Fig. 31 — 2-4 PSK C/N required to achieve a bit error ratio of 10^{-3} in the presence of parabolic group-delay distortion.

—✕— i.f. loop.

—○— earth-station loop (saturated).

—△— transponder loop (transponder 1 dB input back-off, earth-station saturated).

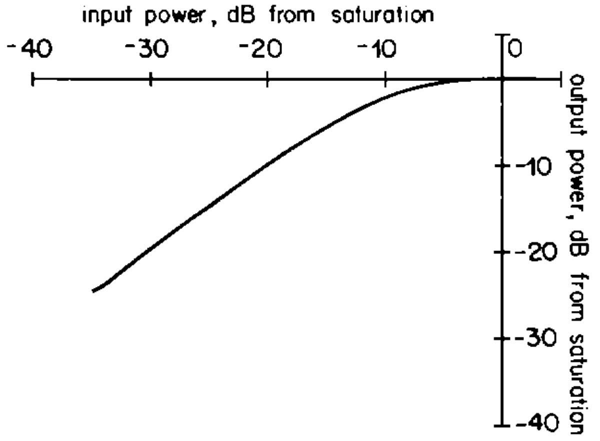

Fig. 32 — Power transfer characteristic of earth-station TWT.

Fig. 30 shows the curve for parabolic amplitude distortion. Extrapolation of the curves indicates that better performance would be achieved with gain at the band edges rather than

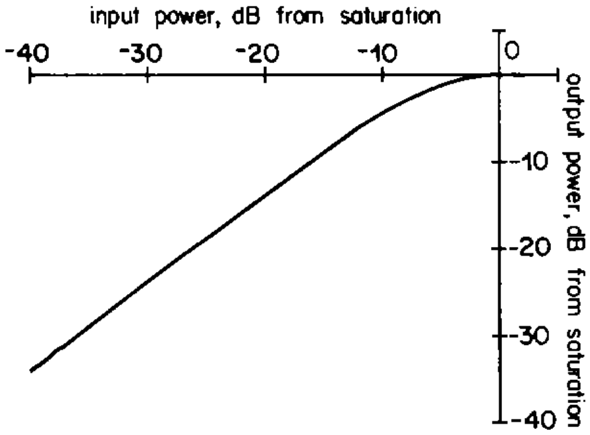

Fig. 33 – Power transfer characteristic of transponder TWT.

loss as introduced here.

Fig. 31 shows the effect of parabolic group-delay distortion. 2-4 PSK does not appear to be sensitive at the levels of distortion available.

The results for distortions introduced into a linear earth-station loop were very close to those for the i.f. loop and so have not been presented here.

In addition, a combination of distortions was added to give some idea of how the distortions interact. Results for a combination of 0.3 dB/MHz, 0.045 dB/MHz^2, 0.6ns/MHz and 0.15ns/MHz^2 are given in Table 9.

Any distortion in the r.f. path may oppose or reinforce the i.f. distortion. Thus other loops could just as well improve the BER as degrade it. This may be a contributory cause to the differences between curves noted in Figs. 26 and 27. Similar comments apply to comparisons of the measured and simulated performance of the channel in the presence of linear and parabolic amplitude and group-delay distortions.

TABLE 9 – Carrier-to-noise ratio (dB) for BER = 10^{-3} with and without distortion.

System	No distortion	Combined Distortion
I.F. Loop	7.8	10.9
Earth-Station Loop (saturated TWT)	7.5	9.1
Earth-Station Loop (linear)	7.8	11.2
Transponder Loop (saturated earth-station)	7.9	9.7
Transponder Loop (linear earth-station)	7.8	11.2

3.2.2.3. Effect of frequency offset of transponder filters on BER

The results of BER may depend on whether or not the 2-4 PSK signal lies centrally in the channel. To determine whether this is a critical parameter an offset of both IMUX and OMUX filters was simulated. As these filters were in fact fixed it was necessary to modify the up-conversion and downconversion frequencies in the earth-station to simulate a frequency drift in the responses of the filters in the satellite.

The values of carrier-to-noise ratio to achieve a 10^{-3} BER for various values of IMUX and OMUX offset are shown in Table 10. Linear distortions were applied at the output of the modulator, giving 0.3 dB/MHz, 0.45 dB/MHz^2, 0.6ns/MHz and 0.15ns/MHz^2 simultaneously.

These figures show that the 2-4 PSK data signal is not very sensitive to the effects of IMUX and OMUX drift. The apparent asymmetry of these results is consistent with the slight offset of IMUX and OMUX filters observed (see Section 3.2.1.).

3.2.3. Subjective appaisal

At the same time that vision quality was being monitored (see Section 3.1.1.) the sound quality was also monitored. Two benchmarks

TABLE 10 — Value of C/N required for 10^{-3} BER as a function of position of signal in the channel

Offset of carrier frequency (MHz)	C/N for 10^{-3} BER (dB)	
	No distortion	Full distortion
−2.0	7.9	9.6
−1.5	7.9	9.6
0	8.0	9.7
1.5	8.1	9.8
2.0	8.2	9.9

were used:

1. When clicks due to errors were first heard in the sound channel.
2. When the sound quality was judged to have degraded to a quality grade of 1.5 in the opinion of the two engineers performing the test. (This was arbitrarily called the failure point in line with such usage within the EBU).

The results are compared with those for the vision signal in Table 1 (See Sec. 3.1.1). The onset of noticeable sound degradation (first clicks) occurred at higher noise levels (lower C/N) than those at which threshold was first noticed in the vision. In this sense the sound channel is more rugged than the vision. However, the BER of the data channel increases rapidly as the noise level increases further, and failure of vision occurred at higher noise levels than failure of the sound. In this sense the vision is more rugged than the sound. The sound and vision performances are therefore closely comparable and which is the more rugged depends on whether emphasis is placed on the high-quality regime or the ultimate failure point.

However, it should be noted that the sound multiplex coding used in these tests does not correspond precisely with any of the options in the EBU C-MAC/packet specification. The performance of the sound channel may be expected to be marginally worse than that expected of the least-rugged but maximum-capacity EBU channel-coding option. It would be improved if, for example, a different "packet-loss" error protection strategy were to be used. In this experiment, the first five most-significant bits of each sample were protected by a single parity bit, and in the event of parity violations in the receiver, a new sample was generated by interpolation. In the event of "packet-loss", the output sampling rate changed to make up for the missing packet, causing "wow" on the output. The failure of the system was thus largely determined by the amount of wow which could be tolerated. Subsequent experience leads to the conclusion that a constant sampling rate is better. Although there are then large audible "clunks" due to "packet-loss", these are less disturbing than the wow introduced by the system used here. Thus slightly better sound performance than indicated in Table 1 may be expected in a future implementation of the EBU system.

3.2.4. A comment on the suitability of 2-4 PSK for DBS

It was the aim of the EBU to devise a DBS modulation system in which the sound failed after the vision. Although dependent upon the sound coding and multiplex option and also the methods of sound and vision demodulation, this was assumed to occur if a digital channel BER of better than 10^{-3} was achieved at 8 dB carrier-to-noise ratio (C/N). There was also a strong desire to achieve good sound quality (say BER better than 10^{-6}) at 14 dB C/N.

Not only was it desirable to be able to achieve excellent performance in an ideal system, but also there should be reasonable reception even if there were moderate channel imperfections.

These tests were the first known opportunity to explore the performance of the proposed satellite broadcast system through a representative, controlled channel. Earlier experiments had been performed either in a linear channel at intermediate frequencies, or using the Orbital Test Satellite (OTS). Transmission through OTS had yielded useful confirmation of the potential of the system, but could not be controlled sufficiently accurately to permit detailed performance evaluations in a representative transmission channel.

The tests reported here confirm that C-MAC is capable of achieving a BER of 10^{-3} at carrier-to-noise ratios of less than 8 dB. However the filtering and demodulator used in the receiver for the sound/data signal must be well-matched to this signal and separate from that optimised for the recovery of the vision signal. The important features are how the BER is modified by typical transmission impairments, e.g. non-linearities and linear distortions. In this context, Table 9 and 10 could be interpreted as saying that the data channel has not met the requirements imposed on it when there are high levels of distortion added. However, it must be emphasised that these levels of distortion are considerably higher than would be found in a practical system. Fig. 34 shows the amplitude and group-delay response of the earth-station (in its linear mode) with full added distortion. In an operational system the amplitude variations would be expected to be noticeably less than 1 dB and the delay variations less than 10ns over the data channel. Figs. 28 to 31 show how the data channel is degraded by other values of distortion. It would appear that the degradation due to the channel will be much smaller than the values indicated by Tables 9 and 10. Indeed, the measurement of the full transponder loop confirmed this. Thus, these measurements not only confirm the suitability of 2-4 PSK in the C-MAC specification for DBS transmission, but also show the range of channel distortions which can be accepted.

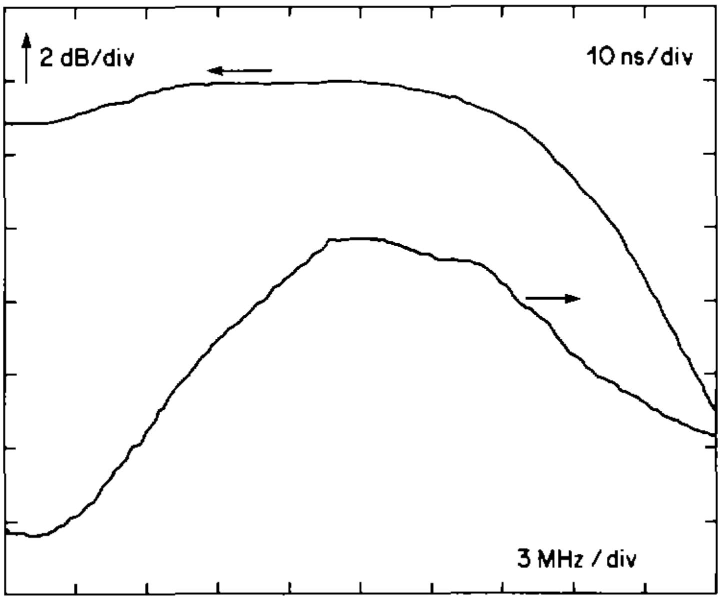

Fig. 34 – Amplitude and group-delay response of the earth-station in its linear mode but with all available amplitude and group-delay distortion added.

3.3. Interference

Some tests had previously been performed with C-MAC to discover its sensitivity to interference and its ability to create interference. Most of these studies have been within the jurisdiction of the EBU and have been particularly directed towards confirming the compatibility of C-MAC with the requirements of WARC 77[3] Broadcast Satellite (Down-link) Plan. This resulted in C-MAC being tested to determine the co-channel interference (c.c.i.) and adjacent channel interference (a.c.i.) requirements in the down-link only. It had been assumed that second-adjacent-channel* interference was negligible and up-link interference was similar to down-link interference.

There was thus a need to complete the tests, looking specifically at second-adjacent-channel interference and up-link interference.

Interference was therefore added to the wanted signal on the up-link. As noted in Section 2, the interference was added at the 14 GHz level having been first amplified in a saturated TWTA in the earth-station. In these tests, the wanted

* A channel whose centre frequency is displaced by ±38.36 MHz from that of the wanted channel.

channel was not subject to non-linear amplification before addition of interference. EBU slide 'Boats' and a pseudo-random binary sequence (p.r.b.s.) were transmitted on the wanted channel. The unwanted channel also carried a p.r.b.s. but with a test waveform (usually pulse and bar) in the luminance channel of the C-MAC signal. The signals in wanted and unwanted channels were not synchronised; this represents the true situation and is more critical than the fixed offset proposed in CCIR Rec 600.

3.3.1. Effect of interference to the vision

The levels at which interference became just perceptible were noted for adjacent and second adjacent-channel interferers. This was done in a darkened laboratory with four skilled observers under conditions which were not precisely controlled. The viewing distance was typically three times picture height. As well as using the designed channel frequencies, the tests were repeated with a slight offset of the frequencies at the satellite input. This gave conditions similar to those which would be experienced with drift of the IMUX and OMUX. A frequency shift of 1.5 MHz was used in a direction which increased the amount of interference.

TABLE 11 — C/I Ratios for just perceptible interference — Interference added on uplink.

Interference type	Carrier-to-interference ratio (dB) for just perceptible interference.
Second adjacent channel (above wanted)	0
Upper adjacent channel	+14
Lower adjacent channel	+12
Second adjacent channel (below wanted)	−8

The point at which the interference caused just perceptible degradation of the wanted channel is given in Table 11, for the case with no additional carrier offset.

It was noticeable that the leading edge of the data burst gave particularly penetrating interference. This may have been due to a fault in the coder used to generate the interference. If this leading edge was ignored, then in the case of the second adjacent channel above the wanted channel, the level of carrier-to-interference (C/I) for just perceptible interference was relaxed to −10 dB. For other interfering channels the limiting interference was not just this leading edge of the data and so no relaxation of C/I was possible. For the second adjacent channels the impairments first seen were from the data only.

When the frequencies of both channels were modified to simulate a drift of IMUX frequency of 1.5 MHz towards the interfering channel there was little change in C/I for just perceptible interference. For upper adjacent-channel interference, the just perceptible level was 14 dB, whilst for lower adjacent-channel interference the level was 13 dB.

The visibility on the picture of adjacent-channel interference (a.c.i.) added to the up-link was similar to that previously observed when added to the down-link. Just perceptible levels of interference occurred in the worst case for the interfering signal 14 dB below the wanted signal. This result is identical to the protection ratio assumed in the 1977 ITU Plan. Thus it appears that a.c.i. can be treated similarly on up-link and down-link. This however, does not include any degradation due to a.m. to p.m. conversion. In theory there is potential for a degradation of 2 to 3 dB with the conversion coefficients found in a high-power TWT. The TWT used here had a low a.m. to p.m. conversion coefficient and so it was not possible to explore this phenomenon experimentally.

For second adjacent-channel interference the up-link protection ratios required ranged from equal levels, to the interferer being 8 dB higher than the wanted carrier (although as noted the first figure may be over-critical). Although the feeder plan has not yet been drafted, one likely plan is a direct frequency transposition of 1977 ITU down-link plan^3, as far as possible. In this instance, UK and Ireland would be allocated second adjacent channels. Thus second adjacent-channel interference at approximately equal levels on the up-link could be expected most of the time. During selective fades the level could easily change unfavourably. There is therefore little margin available in reserve. In these experiments it was the spectral regeneration of the 2-4 PSK signals that caused most interference into the second adjacent channel. The interfering source used a 38 MHz wide pre-filter and was passed through a saturated TWT. This processing causes a large amount of spectral regeneration (see Fig. 10). The regeneration could be reduced by different pre-filtering or reducing the output power of the TWT below saturation. For instance a 27 MHz pre-filter and a reduction in output power of the earth-station of 1 dB gives an improvement of out-of-band radiation of typically more than 5 dB. Alternatively, the regenerated sidelobes could be removed after amplification, say in the earth-station MUX before transmission. The C-MAC specification does call for out-of-band radiation on the up-link to be lower than that achieved in these interference tests. Thus it is reasonable to suggest that lower figures may be achieved in practice and hence the protection margins may be improved. Nonetheless, it must be noted that the IMUX used in the test transponder is specified to have an attenuation of 40 dB at the next-but-one channel centre frequency and at least 30 dB over the whole of that channel. This ensures that the interference effects are predominantly caused by out-of-channel radiation from the interfering carrier. If the IMUX specification is relaxed, then the effect of the interfering carrier itself may have a significant effect.

3.3.2. Effect of interference on the data

As a means of quantifying the effect of interference, the BER of the data in the wanted signal was measured in the presence of a controlled amount of additional noise, added before the C-MAC decoder. The increase in C/N required to maintain a BER of 10^{-3} at the receiver was noted when interference was added at 15 dB C/I ratio.

These tests were carried out using a.c.i. and second-adjacent-channel interference. The change in noise level required to counteract the introduction of interference for a BER of 10^{-3} was 0.1 dB for upper a.c.i. at 15 dB C/I and 0.2 dB for lower a.c.i. at 15 dB C/I. For second adjacent channels there was no measurable change in the 10^{-3} BER when interference was added at C/I of −10 dB. There was no significant change in BER when an IMUX drift of 1.5 MHz was simulated.

These degradations are minimal and indicate that interference to the vision is more important.

3.3.3. The effects of interference on the spectrum

Just as the spectrum of 2-4 PSK is modified by a non-linear amplifier, the spectrum of C-MAC is modified by non-linear amplification in the presence of interference. The effects of spectral regeneration of the 2-4 PSK signal are noted in Section 3.2.1. The spectra of input and output signals were measured for various levels of adjacent- and second-adjacent-channel interference.

Fig. 35 shows a typical signal with upper a.c.i. at the satellite transponder input. Fig. 36 shows a typical output spectra. Although the upper adjacent channel has been reduced in level by filtering there is now evidence of intermodulation products between 10 and 20 MHz below the wanted carrier. This is made clearer in Fig. 37 where the interfering carrier is raised in level to C/I of 5 dB. If a drift of IMUX of 1.5 MHz is simulated, then the spectrum of Fig. 37 is modified to that of Fig. 38. Here more of the interfering carrier itself can be seen.

Fig. 39 shows the spectrum at the input to the transponder with second adjacent-channel interference at a C/I of −10 dB. Fig. 40 shows the spectrum at the output of the transponder. As with a.c.i. there is a residue of the interferer above the wanted carrier and intermodulation products below.

The phenomenon of intermodulation between wanted and interfering carriers is something which has not been fully studied before now. A satellite can generate intermodulation products which although not degrading its own channel can degrade others. For example, consider an Irish satellite receiving its own transmission on channel 6. It might simultaneously receive a UK transmission on channel 4, two channels away. The signals may at this stage be thought of simplistically as the two tones often used for measurements of a.m. to p.m. conversion. After some rejection of the UK transmissions in the IMUX, the signal would be amplified in a saturating TWT. An intermodulation product would be generated at a level which depends on the a.m. to a.m. and a.m. to p.m. coefficients. This intermodulation product would be co-channel with another UK channel on the opposite side of the Irish channel 6, i.e. channel 8. After filtering in the OMUX it would be radiated and cause interference to the bona-fide UK transmission on channel 8. Equally some of UK channel 8 could be radiated on UK channel 4 by the Irish satellite transponder operating on channel 6. To avoid

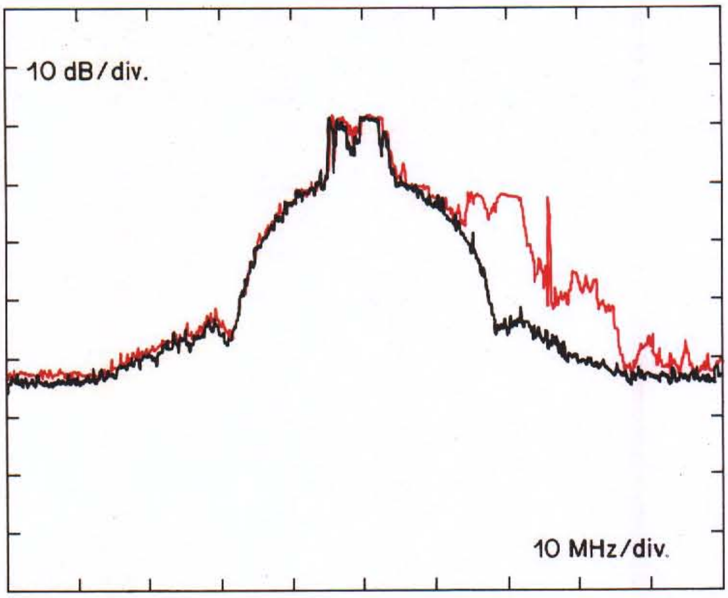

Fig. 35 – Spectrum at input to the transponder for a.c.i. test.

— wanted signal only (a.c.i. at 40 dB down).

— wanted signal with a.c.i. 15 dB below wanted carrier.

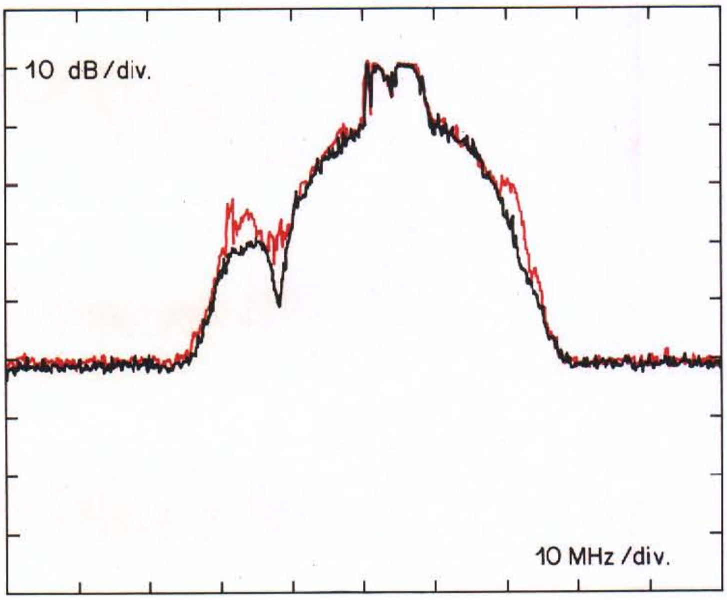

Fig. 36 – Spectrum at output of the transponder with a.c.i. on input as in Fig. 35

— wanted signal only (a.c.i. 40 dB down).

— wanted signal with a.c.i. on input at 15 dB C/I.

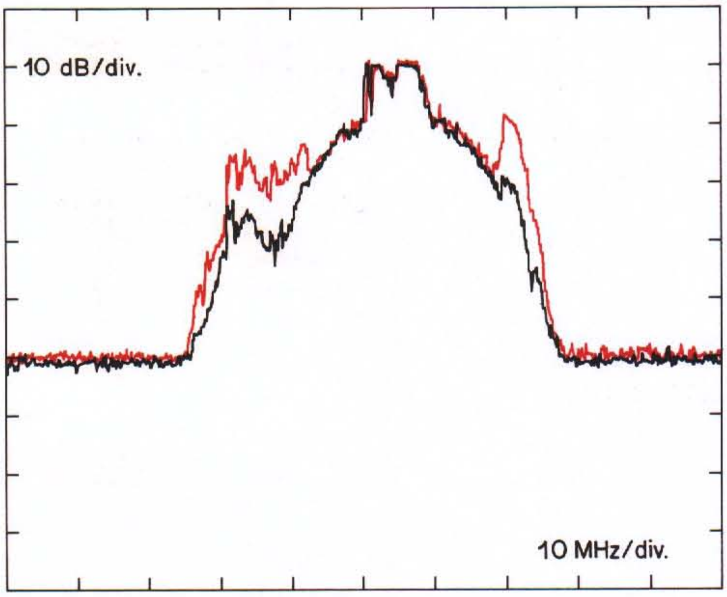

Fig. 37 – Spectrum at output of the transponder with a.c.i. on input.

— with a.c.i. on input at 5 dB C/I.

— with a.c.i. on input at 15 dB C/I.

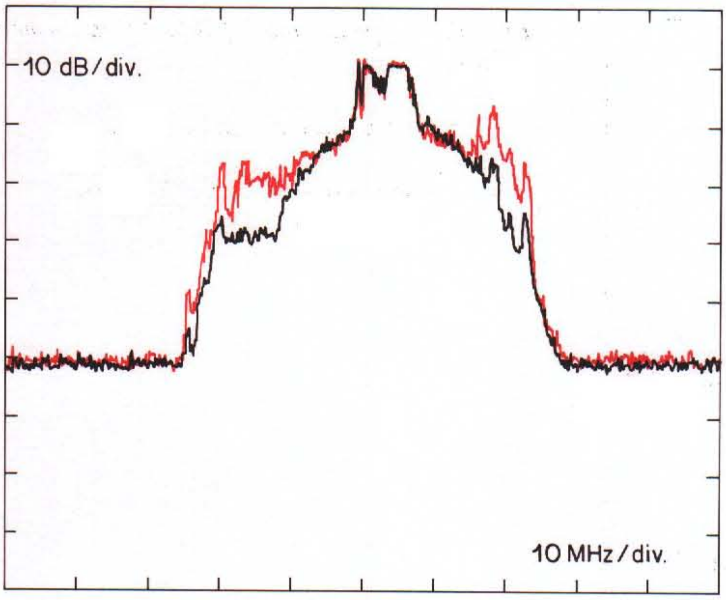

Fig. 38 – Spectrum at output of the transponder with simulated drift of IMUX and OMUX by 1.5 MHz and a.c.i. on input as in Fig. 37.

—— with a.c.i. on input at 5 dB C/I.

—— with a.c.i. on input at 15 dB C/I.

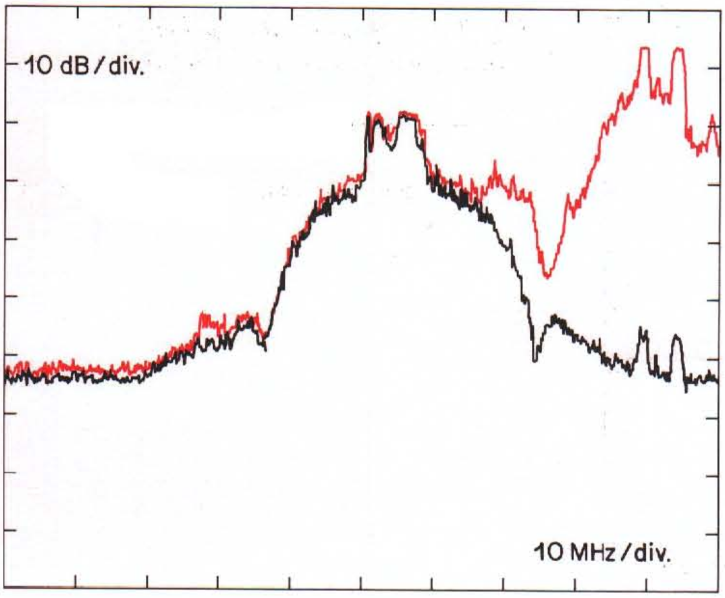

Fig. 39 – Spectrum at input to the transponder with second adjacent-channel interference.

—— wanted signal only (a.c.i. 40 dB down).

—— second adjacent-channel interference 10 dB above wanted carrier.

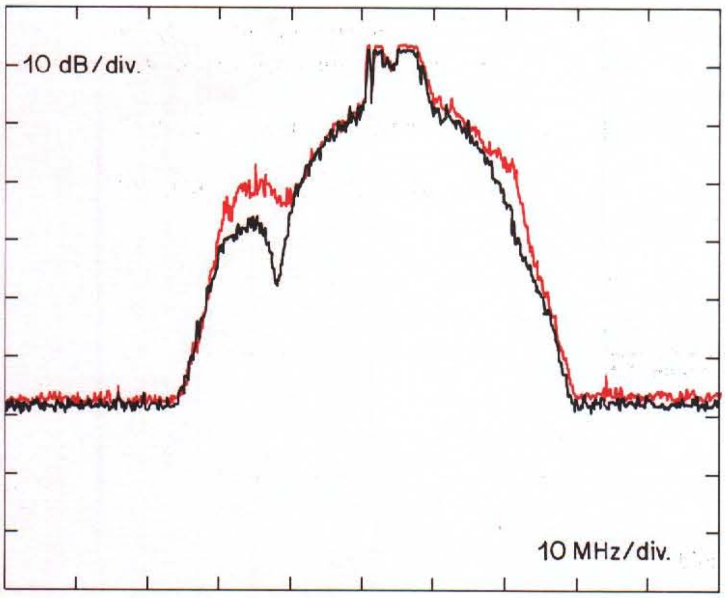

Fig. 40 – Spectrum at output of the transponder with second adjacent-channel interference on the input as in Fig. 39.

—— wanted signal only (a.c.i. 40 dB down).

—— second adjacent-channel interference on input at –10 dB C/I.

transmitting noticeable interference in other DBS channels it is desirable that the combined effects of IMUX, OMUX and TWT ensure that the e.i.r.p. of the interference is maintained at least 40 dB below that of the bona-fide signal. This inevitably requires IMUX and OMUX filters to provide high attenuation at second adjacent-channel frequencies, as is the case with this experimental breadboard transponder.

4. Conclusions

C-MAC has been transmitted under strictly controlled conditions through a complete simulated DBS chain, comprising an earth-station transmitter, a breadboard DBS transponder and an earth-station receiver.

During the tests the picture and data quality were good. There was little sensitivity to transmission impairments of the type and magnitude likely to be found in practice. It was only when large transmission-channel impairments were introduced that the data channel was excessively degraded. With the same transmission impairments vision quality remained good; the most noticeable degradation was a variation in baseband frequency-response.

The tests demonstrated the potential that exists for unwanted spectral regeneration. This took the form of regeneration of sidelobes of the data spectrum and generation of extra interference in the presence of adjacent-channel interference. The level of this interference could be controlled by varying operating point of the TWTs in the system and by suitable choice of filtering at source and in the satellite.

The results confirmed the suitability of C-MAC as a transmission standard for satellite broadcasting.

5. Acknowledgements

The author would like to thank British Aerospace P.L.C. for providing the breadboard satellite transponder and measurement equipment for these tests, and C. Stickland, C. Barber and R. Jayes of the same company for much assistance.

He would also like to thank the European Space Agency for the loan of the i.f. distortion unit, and Dr. R.A. Harris for valuable discussions on modulation systems.

C. Gandy, R.P. Ritchie and C. Spicer provided invaluable assistance in conducting the tests which is very much appreciated.

He would further like to thank other colleagues too numerous to mention individually in the BBC Research, Designs, and Television Outside Broadcasts, Communications and Transmitter Departments for their willing assistance in the preparations for these tests.

6. References

1a. CCIR, 1983, Television standards for the broadcasting-satellite service. CCIR Report AA/10-11. Conclusions of the interim meetings of Study Groups 10 and 11, Geneva 1983.

1b. MERTENS, H., *and* WOOD, D., 1983: The C-MAC/packet system for direct satellite television. EBU Review - Technical No. 200, August 1983.

2. DUPONTEIL, D., 1981: Binary modulations for digital satellite communications link with differential demodulation. Fifth International Conference on digital satellite communications, Geneva, March 1981.

3. INTERNATIONAL TELECOMMUNICATIONS UNION, 1977. World Broadcasting-Satellite Administrative Radio Conference, Final Acts, Geneva 1977. (This information is reproduced with minor amendments in the Radio Regulations, 1979, Appendix 30).

4. STICKLAND, C., *and* BARBER, C.P., 1984: Breadboard payload for DBS satellites. IEE Conference publication No. 240, International Broadcasting Convention, Brighton, September 1984.

5a. HARMAN, M.W., *and* SCOTT, J.M.C., 1982: Transportable satellite terminal for television programme contributions. IEE Conference publication No. 220, International Broadcasting Convention, Brighton, September 1982.

5b. HARMAN, M.W. *and* GANDY, C., 1984: A transportable satellite earth station. BBC Research Department Report 1984/8.

6. WEAVER, L.E., 1971: Television video transmission measurements. Ebenezer Baylis, Leicester, June 1971.

7. LEWIS, N.W., 1954: Waveform responses of television links. Proc. IEE, Vol. 10, Part II, No. 72, pp. 258-270.

Printed by BBC RESEARCH DEPARTMENT, Kingswood Warren, Tadworth, Surrey, KT20 6NP